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RESEARCH REPORT

DRYING OF WALLS WITH VENTILATED
STUCCO CLADDING:
A PARAMETRIC ANALYSIS

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DRYING OF WALLS WITH VENTILATED STUCCO CLADDING: A PARAMETRIC ANALYSIS

by
Donald M. Onysko
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ABOUT THIS REPORT

Canada Mortgage and Housing Corporation (CMHC), the federal government's housing agency, is responsible for administering the *National Housing Act*.

This legislation is designed to aid in the development of housing and living in Canada. As a result, CMHC has interests in all aspects of housing and urban growth and development.

Under Part IX of this Act, the Government of Canada provides funds to CMHC to conduct research into the social, economic and technical aspects of housing and related fields, and to undertake the publishing and distribution of the results of this research. CMHC, therefore, has a statutory responsibility to make widely available, information which may be useful in the improvement of housing and living conditions.

This publication is one of the many items of information published by CMHC with the assistance of federal funds.

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- John Gusdorf was preparing a review of the documentation for WALLDRY and other programs in Canada Mortgage and Housing Corporation files when this study was initiated. He was able to locate certain documents and records that were previously unknown to the author that helped considerably.
- Mike Swinton, the prime originator of the computer program when it was first prepared and the subsequent modifier of the program for laboratory studies when he joined the Institute for Research in Construction (IRC), had excellent memory recall about the program and the algorithms built into it that puzzled the writer. He was able to clear up questions that allowed the work to proceed.
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- Thanks are also due to Theresa Weston at Dupont who provided information on the properties of some of their air barrier membranes.
- Finally, Peter Harco at Hal Industries Inc. provided information on the properties of some of their building papers, and conducted a special side study to determine the maximum moisture content of those papers.

EXECUTIVE SUMMARY

A parametric study of stucco clad wall systems was undertaken to help understand the drying behaviour of outer wall venting systems and to determine which systems would be worth investigating in an experimental test program by the Envelope Drying Rates Analysis Consortium (EDRA). In the course of the investigation, additional questions arose about how the study would be conducted, and simulations were provided to help guide the test program.

The main objective was to study ventilation cavity parameters for stucco wall systems using WALLDRY, a computer program developed by Canada Mortgage and Housing Corporation (CMHC). A significant number of combinations of ventilation cavity depths and vent gap heights were included to assist the EDRA steering committee to decide on the final parameters for the experimental work. The following findings are noted for simulated drying of walls that were initially very wet.

1. The predominant detail affecting the rate of drying is the ventilation cavity depth behind the stucco. The vent gap height was not as critical to the rate at which moisture was removed.
2. The decoupled stucco cases (by specifying the properties of the stucco to be non-absorbent) provided a lower bound solution to the investigation. Some types of stucco/backing systems approach this case. The drying rates were found to be slower than when the stucco was directly coupled to the wall (i.e., when the properties of the inner layer of stucco facing the wall were the same as for the outer face, and there was no intended restriction to moisture flow through the stucco).
3. The coupled stucco case permitted both ventilation and diffusion of moisture to occur. When the stucco was applied directly to the building paper against the wood sheathing, only diffusion permitted loss of moisture from the wall.
4. Closing the top vent of a vented stucco wall slowed drying significantly. However, it was demonstrated that even a slight amount of leakage (e.g., that permitted by a 1-mm vent gap) was sufficient to approach the drying capability of a vented cavity with equal top and bottom vents.
5. From an experimental point of view, it was demonstrated that the moisture conditions of the stucco at the beginning of the study could interfere with the interpretation of the drying rates of the wood wall behind. This was because the stucco could absorb or desorb large quantities of moisture depending on the equilibrium state of the stucco before exposure to the test chamber conditions. In other words, the total weight change of a wall does not provide all the information needed to characterize the drying capability of the wall.
6. The use of a lower relative humidity (RH) condition in the chamber speeded drying of the test walls. A range of conditions from 50 per cent RH to 80 per cent RH was examined to allow the EDRA team to decide whether a change in planned chamber conditions was warranted. A similar parametric evaluation was done for the temperature of the chamber representing the outdoor conditions.
7. Removal of the polyethylene vapour barrier allowed relatively rapid drying of the wall for the conditions simulated. It was concluded that for a one-time construction moisture load, this might permit drying to take place during

construction provided the final painting was not done until the moisture had escaped. Chronic wetting of walls not having polyethylene vapour barriers is another matter entirely.

8. Vinyl siding appeared to retain the moisture in the sheathing for a significantly longer time than many coupled stucco walls. These simulations did not include the effect of ventilation provided by starter strips or other practical closure details that might be found in the field—details that would improve the drying performance of walls. It was suggested that consideration to some venting would be beneficial for vinyl clad walls. Pumping mechanisms related to the ability of the wind to flex the siding probably improves the drying capability of vinyl siding. Some research is probably justified in characterizing the equivalent leakage properties of these joints.
9. A wall with primed and painted wood siding applied directly to the building paper experienced as poor drying as the vinyl siding clad wall. In addition, direct contact with the wall allowed the siding to accumulate moisture. It has long been known that this can lead to degradation of the siding and prevent drying of the backup wall.
10. The wall with primed and painted wood siding installed on batten strips and with vents provided at the bottom and limited venting at the top experienced good drying. It also maintained the moisture content of the wood siding at moderately low levels.
11. The controlling element for moisture flow in all the parametric runs was the wood sheathing. The properties of the oriented strand board (OSB) material were assumed from information available in the literature. More recently, unpublished work suggests that the properties of the OSB can vary significantly from one manufacturer to another. Consequently, the wood sheathing type and manufacture are critical matters to consider in choice of materials for the experimental work.
12. Plywood sheathing has higher permeability than the OSB, based on the test values available in the literature. Due to the manner that initial moisture conditions were specified (in terms of bulk density), a comparison between them was not quite appropriate. However, it was concluded that plywood sheathed walls would probably dry more rapidly.
13. In the same vein, a comparison between the drying of 2 x 4 (38 x 89 mm) vs. 2 x 6 (38 x 140 mm) framed walls was complicated by the difference in total volume of wood framing and the total moisture that would be held in the wood for the same initial moisture content conditions. This comparison is appropriate when dealing with construction moisture, in which case it was shown that a much greater volume of water had to be dissipated, and the concentration of that moisture in the sheathing was higher and it took longer to dry.
14. The moisture content of the wood framing can change rapidly at the beginning of the experiment, and it is necessary to be able to characterize the initial moisture gradients in the lumber. The variation in moisture up and down the wall is not expected to be very large in the lumber framing. However, drying from the bottom plate is expected to be slow. This was not modelled specifically in this study; however, based on the temperature gradients as a result of movement of air behind the stucco cladding, the lower part of the test walls will dry more slowly than the top under the test conditions simulated.
15. The moisture gradients through the thickness of the sheathing will be high. There will also be vertical moisture gradients in the sheathing due to the manner that moisture escapes at the top of the ventilation space, if there is one.
16. The moisture content and absorption properties of the stucco will be important influences on the weight measurement of the test walls. Any changing chamber conditions that affect the absorption and desorption of moisture from the stucco may swamp the

smaller changes in moisture content of the framing and sheathing of the test walls. In this case, if attempts to simulate solar effects are made, while the walls may dry more rapidly, there will be far more complex moisture redistribution taking place. That would need to be adequately monitored for comparison with computer simulations, and to attribute weight changes appropriately.

17. Application of a simulated moderate wind speed inside the test chamber directed at the bottom vents resulted in greater cooling of the outer portions of the test walls. This slowed the rate at which moisture could be lost by venting. The lower drying rate was not large. Much depends on the airflow characteristics of the ventilation cavity and the vent gaps actually employed.

Some improvements to the model were recommended. Most important is that the database on material properties be examined and made current. The WALLDRY computer model does not currently include liquid mass transfer. Inclusion of this capability is likely warranted. Comparison of predicted drying with that by more capable models is also worth pursuing.

While the computer simulations described in this report correspond with general preconceptions of how walls perform under different conditions, it is only when verification studies are conducted that deficiencies in a model can be assessed and the model improved. The main concluding recommendation was that it was important to know the physical properties of the materials used in an experimental program. Knowing the initial boundary conditions and the airflow characteristics of the ventilation system for walls are critical to understanding how the walls perform under laboratory conditions and, by extrapolation, how they might perform under real weather conditions in the field.

TABLE OF CONTENTS

1 OBJECTIVES	1
2 INTRODUCTION	2
3 LIMITATIONS IN SCOPE OF THE WORK	3
4 MODIFICATIONS TO WALLDRY	4
5 INITIAL PROPOSED SIMULATION PLAN	6
Simulation of Steady State Thermal Drive	6
Simulation of Steady State Infiltration/Exfiltration	6
6 DEFINITION OF TEST WALLS AND CONDITIONS	8
Initial Moisture Content	8
The Interior RH and Temperature	8
The Exterior RH and Temperature	8
Framing Lumber	8
Insulation	9
Double Plates Top and Bottom.....	9
Interior Wall Facing	9
Exterior Sheathing: 12.5-mm OSB	10
Sheathing Paper and Sheathing Membranes	10
Spacing of Batten Strips.....	10
Continuous Weighing and Moisture Loss Mechanisms	10
Stucco	10
Neutral Pressure Test	11
Wind Pressure Differentials	11
7 AIR LEAKAGE CHARACTERISTICS	13
Air Cavity Flow Characteristics	13
Air Leakage Characteristics Through Top and Bottom Vents.....	15
8 MATERIAL PROPERTIES	18
9 REVISED PARAMETRIC PLAN	20
10 RESULTS.....	23
Decoupled Stucco Walls.....	23
Coupled Stucco Walls.....	26
Performance of Reference Walls	42

11 CONCLUSIONS	47
12 SUMMARY	50
13 RECOMMENDATIONS FOR FURTHER STUDY	51
APPENDIXES	
A: TYPICAL INPUT WALL FILE	A-2
B: TYPICAL INPUT WEATHER FILE	B-2
C: DATABASE OF MATERIAL PROPERTIES - PROPS.DAT.....	C-2
BIBLIOGRAPHY	61

LIST OF FIGURES

Figure 1:	Solution of crack flow equation for straight-through cracks, from Etheridge	13
Figure 2:	Diffusion resistivity as a function of relative humidity for several materials implemented in WALLDRY	18
Figure 3:	The effect of RH conditions in the chamber on the weekly drying rates as a function of the ventilation cavity depth for a vent gap size of 2.5 mm - decoupled stucco, $T = 5^{\circ}\text{C}$	24
Figure 4:	Effect of temperature in the chamber on the weekly drying rates as a function of ventilation cavity depth of a vent gap size of 2.5 mm, decoupled stucco, $\text{RH} = 50\%$	25
Figure 5:	The effect of RH conditions in the chamber showing the effect of ventilation cavity depth on weekly drying rates when stucco is coupled, vent gap size 2.5 mm, $T = 5^{\circ}\text{C}$	28
Figure 6:	Total weight change expected to take place under different conditions for wall S19-12	29
Figure 7:	Total weight change expected to take place under different conditions for wall S38-12	29
Figure 8:	Drying from each of the major elements of wall S19-12, with the 12-mm vents open at the top and bottom, chamber conditions 7% RH and 5°C with the stucco preconditioned at 50% RH.....	30
Figure 9:	Drying from the shell and core of wood framing, top and bottom vents open for wall S19-12, chamber conditions at 70% RH and 5°C , stucco initially preconditioned at 50% RH	31
Figure 10:	Drying of the inner face layer of OSB sheathing for wall S19-12 with 12-mm vents open top and bottom, chamber conditions at 70% RH and 5°C with the stucco preconditioned at 50% RH	31
Figure 11:	Drying of outer layer of OSB sheathing for wall S19-12 with top and bottom vents open at 12 mm, chamber conditions at 70% RH and 5°C with stucco preconditioned at 50% RH	32
Figure 12:	Drying from each of the major elements in wall S19-12, with the top vent closed, chamber conditions at 70% RH and 5°C with stucco preconditioned at 50% RH	33
Figure 13:	Drying of the outer shell and inner core of the lumber framing, wall S19-12, chamber conditions at 70% RH and 5°C , stucco initially preconditioned at 50% RH	34
Figure 14:	Drying curve for the inner face layer of OSB sheathing for wall S19-12 with the top vents closed, chamber conditions at 70% RH and 5°C with the stucco preconditioned at 50% RH	34
Figure 15:	Drying of outer layer of OSB sheathing in wall S19-12 with the open top closed, chamber conditions at 70% RH and 5°C with the stucco preconditioned at 50% RH	35
Figure 16:	Drying from each of the major elements in wall S19-12, with the top vent partially closed gap (1 mm), chamber conditions at 70% RH and 5°C with the stucco preconditioned at 50% RH	35
Figure 17:	Drying curve for the inner face of the OSB sheathing, wall S19-12, with the top vent partially closed gap (1 mm), chamber conditions at 70% RH and 5°C with the stucco preconditioned at 50% RH	36
Figure 18:	Drying of outer layer of OSB sheathing in wall S19-12, with the top vent partially closed gap (1 mm), chamber conditions at 70% RH and 5°C with the stucco preconditioned at 50% RH	36
Figure 19:	Drying of the main elements of the wall S19-12 with lumber framing, chamber RH of 50% and stucco cladding initially preconditioned to the same RH conditions	39
Figure 20:	Moisture buildup in the inner layer of the OSB sheathing, wall S19-12 with 2 x 6 lumber framing, maximum moisture that could be held specified to be 45%	39
Figure 21:	Drying from each major element in wall S19-12, polyethylene vapour barrier removed and top vent closed, chamber conditions at 70% RH and 5°C with stucco initially preconditioned at 50% RH.....	40
Figure 22:	Drying of the outer shell and inner core of lumber framing, wall S19-12, polyethylene vapour barrier removed, top vent closed, chamber conditions at 70% RH and 5°C with stucco initially preconditioned at 50% RH	40
Figure 23:	Drying curve for the inner face of the OSB sheathing, wall S19-12, polyethylene vapour barrier removed and top vent closed, chamber conditions at 70% RH and 5°C with stucco initially preconditioned at 50% RH	41
Figure 24:	Drying of outer layer of OSB sheathing in wall S19-12, polyethylene removed and top vent closed, chamber conditions at 70% RH and 5°C with stucco initially preconditioned at 50% RH	41

Figure 25:	Vinyl siding wall, drying from each of the major elements, chamber conditions at 70% RH and 5°C.....	43
Figure 26:	Drying from each major element in wall S19-12, polyethylene vapour barrier removed and top vent closed, chamber conditions at 70% RH and 5°C with stucco initially preconditioned at 50% RH.....	43
Figure 27:	Drying from each major element in a wall with strapped wood siding with a 19-mm ventilation cavity, a 12-mm bottom vent and a 1-mm top vent, chamber conditions at 70% RH and 5°C with stucco initially preconditioned at 50% RH.....	44
Figure 28:	Relative humidity of air in the ventilation cavity, bottom to top, chamber RH of 70%.....	45
Figure 29:	Drying of outer shell and inner core of the lumver framing, wall with wood siding on 19-mm batten straps, 12-mm bottom vent and 1-mm top vent	45
Figure 30:	Drying curve for the inner face of the OSB sheathing, wall with wood siding on 19-mm ventilation cavity, 12-mm bottom vent and 1-mm top vent	46
Figure 31:	Drying of outer layer of OSB sheathing in wall with wood siding on a 19-mm ventilation cavity, 12-mm bottom vent and 1-mm top vent.....	46

LIST OF TABLES

Table 1:	Original experimental plan to study the influence of venting on drying.....	6
Table 2:	Ventilation cavity depth/vert gap height set (21 combinations).....	16
Table 3:	Flow coefficient K_2 for ventilation gaps formed by the top and bottom flashing for a 1-m length of gap [$\text{Pa}/((\text{L}/\text{min})/\text{m}^2)$]	17
Table 4:	Flow coefficients K_1 and K_2 for the ventilation cavity element height = 0.26667 m element width = 1 m.....	17
Table 5:	Effect of ventilation parameters and chamber RH on the weekly drying rate ($\text{g}/\text{m}^2/\text{week}$) neutral pressure, decoupled stucco, chamber temperature 5°C	23
Table 6:	Effect of ventilation parameters and chamber temperature on the weekly drying rate ($\text{g}/\text{m}^2/\text{week}$) neutral pressure, decoupled stucco, chamber RH = 50%.....	25
Table 7:	Effect of ventilation parameters and chamber RH on the weekly drying rate from wood framing ($\text{g}/\text{m}^2/\text{week}$) neutral pressure, coupled stucco, chamber temperature 5°C	27
Table 8:	Net drying from stucco as a function of vent characteristics and chamber RH ($\text{g}/\text{m}^2/\text{week}$) neutral pressure, coupled stucco, chamber temperature 5°C	27

1. OBJECTIVES

The objective of this work was to undertake a parametric evaluation of test parameters intended for study in the Canada Mortgage and Housing Corporation (CMHC) B.C. Coastal Wood Frame Envelope Design Test Program. This report details the findings for steady-state laboratory conditions with different thermal and relative humidity (RH) conditions.

Specific objectives are:

- to study which ventilation cavity thicknesses are worth evaluating by laboratory testing;
- to study which venting restrictions (at the top and bottom) that have been proposed for study by the CMHC research plan have a useful effect;
- to assess the relative ranking of ability to dry for a particular temperature and relative humidity history; and
- to assess the effect on drying under these conditions when the vapour barrier is removed.

2. INTRODUCTION

The original proposed CMHC test program involved a significant number of test walls of a specific type with different venting parameters (Hazleden, 1997). In a review of that proposed test program, it was recommended that computer modelling be employed as much as possible to determine which walls were worth testing to confirm the design approach (DMO Associates, 1997). The number of parametric combinations involving ventilation cavity thickness and the different venting restrictions, together with the inclusion of conventional vinyl and wood siding walls for comparison, resulted in over 40 test walls requiring simulation.

As the time required for significant drying to take place is important to know for laboratory experiments, computer simulation can provide an estimate of the drying time. This time affects both the planning and cost of the laboratory experiments. In turn, the experimental results can be used to assess the ability of computer models to mimic the behaviour of the real test walls, providing sufficient measurements are taken to confirm the simulations. Since ranking of walls may only hold for the given conditions, it is probably necessary to examine the behaviour of walls under varying weather conditions to arrive at a fuller appreciation of likely performance in the long run. This can only be done practically with models both for prediction and design using real weather conditions.

The two computer programs considered for this work were WALLDRY, a model developed on behalf of CMHC, and LATENITE, a more recent model developed by the Institute for research in Construction (IRC). The WALLDRY program is not considered as flexible or accurate as LATENITE, but it was foreseen that, for the purposes of this preliminary work, it would be sufficiently accurate.

While this simulation work got under way, plans to pursue the experimental work proceeded. The project was named the Envelope Drying Rates Analysis Experiment (EDRA). Start-up funds were provided by CMHC, and a consortium of private and public funding partners was assembled. The project is being planned and executed at the Forintek Canada Corp. laboratory in Vancouver. During the planning phases into the testing methodology, with the advice of the steering committee and a technical team sub-group, a significant number of changes were made to the original plan. Consequently, the scope of this parametric analysis and the contents of the report were modified to provide answers to some questions that arose in planning the study and to assist in finalizing the test parameters.

It is worth noting that the planned experimental program will be conducted with the test walls set into the walls of a chamber, the inside of which is conditioned to represent outdoor relative humidity and temperature conditions. The laboratory in which the chamber will be built will provide the "indoor" conditions. These "indoor" conditions vary somewhat, but based on recordings of conditions taken over time, the variation is not expected to affect the results substantially.

3. LIMITATIONS IN SCOPE OF THE WORK

Despite the clear objectives, it is useful to identify the limitations in the scope of this parametric study. These limitations have relevance concerning the generality of the results that will be obtained, and it is useful to bear these in mind from the beginning.

- The main objective is to study the venting ability of different ventilation cavity widths.
- Only one specific wall construction has been chosen for the main parametric study. Use of different constructions would lead to different drying rates and venting capacities.
- The material properties used, in the main, were those built into the WALLDRY database in the 1980s. Some have been revised based on more current literature. No assessment of the effect of variability, or even of their validity, will be made.
- The laboratory "weather" conditions chosen are relatively mild and will lead to a specific relative ranking of wall drying that may not hold under more severe conditions or under real weather conditions.
- A wall achieving a high ranking in its ability to dry may not necessarily be an appropriate wall to build in the Vancouver area under summertime conditions when air conditioning may be required.

To assist in the planning of the experimental work, several additional parameters are included that were not specified in the original scope. They will be identified further in the report.

Changes to the WALLDRY program were not originally identified as necessary to accomplish this work. It was only after the project was initiated and past applications of the model were reviewed that changes to the model to handle these particular cases were found to be required. Changes were incorporated into the computer model to simulate, more realistically, expected performance. Laboratory experimentation is quite expensive, and a change in the scope of the project to accommodate this was merited.

Many questions about wall performance were identified that would be useful to pursue through parametric analysis. Only some questions can be accommodated within the scope of this study beyond those originally identified.

4. MODIFICATIONS TO WALLDRY

The current version of WALLDRY delivered to CMHC by RWDI and Scanada in 1988 is a user-friendly version of the simulation model that was prepared to simplify the input properties for users of the model. Before preparation and delivery of the user-friendly version, the input data had to be prepared manually into a file that the main computing portion of the model recognized and executed. This computer model uses one-year weather data files prepared by RWDI from Environment Canada weather tapes for 10 Canadian cities across the country.

A second version of the WALLDRY model was prepared to investigate the performance of walls in laboratory tests for the 1989 study by Morrison Hershfield (1999a, b). The laboratory "weather" file included air leakage parameters to permit the study of infiltration and exfiltration of air, as well as accepting an input file for hypothetical test conditions or for the actual laboratory conditions experienced by test walls. This laboratory version of WALLDRY formed the basis for further modifications involved in the current study. In this report, we continue to refer to the model as WALLDRY without indicating the specific version.

There are a number of limitations to the user-friendly version of WALLDRY and its subsequent versions. A recent review of the development of WALLDRY outlines those limitations and how some investigators, from past CMHC research projects, have attempted to overcome them (Gusdorf, 1998). In the present report, only four limitations are mentioned.

- The program modules are written in QuickBasic and run under DOS. The modules are sizable, and are too close to the memory limit for DOS to allow the code to be changed significantly while still allowing the program to be compiled.
- The diffusion properties of the building materials involved are not sensitive to the current moisture content of the materials.

- The only sorption isotherm built into the model is for wood. All materials identified as wood-like (or hygroscopic) are treated identically.
- Liquid mass transfer is not accommodated for.

On examining the research reports in which the WALLDRY predictions were compared with test measurements, it was clear that some improvements should be included. Improvements previously entertained in the various studies done for CMHC were found to be insufficiently effective or were too arbitrarily made. WALLDRY itself was not intended to be a detailed scientific analytical tool. There will always be some inaccuracy in predictions because not all properties or the interaction between materials can be predicted.

In modifying the code, the size limitation barrier was quickly reached. The program modules could not be compiled unless only minor changes were made. However, it was possible to add additional code when the model was run in the interpretative mode. The program takes moderately longer to run in this mode.

The user-friendly modules could not be used to create or adapt an input data file without making substantial program changes to each sub-module to accept a stucco clad wall as input. For this study, changes to the input file were made manually for each case, and the main computing module WALLCALC, as modified for this investigation, was used for the analysis. In this form of operation, WALLDRY is no longer user-friendly. Portions of the user-friendly sub-modules are still required to read the input data file and prepare the input module WALLDRY.TRS for WALLCALC to read and analyze. Conversion of WALLDRY to run under some other, less limiting, operating system that would overcome memory limitations was considered to be beyond the scope of the current project.

Once the decision was made to run the program in the interpretative mode, sorption isotherm algorithms were developed for a significant number of materials listed in the material property database. These were incorporated in the sub-routine *PartialPressure*.

A new sub-routine, *UpdateVaporDiff*, was written to define and update the diffusion properties of the relevant materials to account for the influence of moisture content on those properties on an hour-by-hour basis. The diffusion properties were recalculated hourly using the moisture contents calculated for the current hour.

A new sub-routine, *MoistureRemoval*, was written to locate and tally the total quantity of, and manner in which, moisture was removed or redistributed within the wall.

The properties of one type of stucco were added to the property database. The material was recognized within the program and the diffusion resistivity and sorption isotherms for that material were added in the appropriate sub-routines.

The version of WALLDRY which had been adapted for comparison with laboratory test conditions introduced the ability of the program to deal with infiltration and exfiltration (Morrison Hershfield, 1991a). In the process, the changes affected the ability of the program to account for varying wind pressures on the exterior face of test walls (i.e., on the side facing simulated exterior conditions). The original version of WALLDRY was designed to accept weather data files generated from

Environment Canada weather tapes in which wind speed and direction were included. To accept simulated wind pressure differentials on that face of the test walls, it was necessary to reintroduce and adapt the original computer code, and to provide wind pressure coefficients that would mimic the intended experimental protocols. The EDRA test protocol involves applying a flow of air between 1.0 and 2.0 m/s against the bottom of the test walls, and to attempt to maintain a pressure differential of 1 Pa between the top and bottom of the walls. These conditions were simulated by specifying a wind speed of 1.5 m/s and introducing wind pressure coefficients into the input files so the pressure at the top of the wall was 1 Pa different than at the bottom. This maintained the ability of the computer program to account for overall pressure differences across the walls for infiltration/exfiltration effects. The effect of applying airflow against the wall is treated as a separate issue in this parametric study.

The thermal resistivity of the building materials in the database is currently treated as a constant, except for changes introduced in the body of the program. No change was made in the program to account for the influence of moisture content on the thermal resistivity of materials. While thermal resistivity is influenced by the moisture content of the materials, this was considered to have less impact on the performance of the model than the changes described above. A property that may have a more significant impact concerns the liquid diffusivity of the materials. Adding the effect of this property to the program was considered well beyond the scope of this project.

5. INITIAL PROPOSED SIMULATION PLAN

Simulation of Steady-state Thermal Drive

The initial proposed CMHC experimental test plan outlined cases involving five cavity dimensions (both inside and outside of the sheathing), and six vent areas as a percentage of the wall area. The

matrix of proposed tests for a typical ventilated cladding case shown in Table 1 includes 20 walls. Including the case of venting behind the sheathing membrane and some reference walls (vinyl siding and wood siding, both furred and non-furred), there were 43 cases for study.

Table 1: Original experimental plan to study the influence of venting on drying

Vent Gaps % of Wall Area	Venting Cavity Depth (mm)				
	38	19	12	5	2.5
0	N/A	N/A	N/A	N/A	N/A
0.1	*	*	*	*	*
0.2	*	*	*	*	*
0.4	*	*	*	*	N/A
0.8	*	*	*	N/A	N/A
1.6	*	*	N/A	N/A	N/A
3.2	*	N/A	N/A	N/A	N/A

The walls having ventilation spaces inboard of the sheathing, while not currently considered feasible for a membrane-type separator between the cavity and the insulation, may be simulated. A membrane can be specified instead of wood sheathing for that layer position, and the wood sheathing backing the stucco can be incorporated into the properties of a composite cladding involving sheathing with stucco attached to it. The potential advantage of this cavity arrangement is that moisture loss (or gain) can be more rapid. In this case, the separator membrane controls the rate of moisture loss. But, there are practical difficulties in detailing the flashing. If we assume that the practicality of this arrangement may be solved by innovative material selection, then it may become a valid class of wall to study. However, this condition was considered less important for simulation than others required for this study and was not included.

Simulation of Steady-state Infiltration/Exfiltration

The proposed CMHC test program involved study of pressure differences leading to infiltration and exfiltration of air. This situation can be used to study the potential wetting or drying of a wall. The proposed test program originally involved introduction of sequential infiltration and exfiltration pressure modes of the same duration as for the steady-state drying at neutral pressure. However, since then, the merits of inducing a positive or negative pressure difference across the test walls have been questioned as a means of evaluating the drying capability of walls.

Consequently, the parametric plan followed in this study de-emphasizes the infiltration and exfiltration modes as part of the main test objectives. The benefit of this test protocol was not readily apparent regarding the tests done by Morrison Hershfield (1991a). The drying was

quite slow to begin with, and before it progressed sufficiently, the conditions changed. Unless the moisture losses can be measured with sufficient accuracy, there is little point in doing this experimentally even though the modelling can be done. The exercise is, to a very considerable degree, a good test of the capability of a model. But, other questions require investigation first.

What is the implication if, for a particular defect, movement of air into and out of the wall is possible and drying is improved? For it to be an effective construction addition, it would have to exist for each cavity in equal measure. Currently, if the air tightening of the building envelope is poorly done (or not done at all), there is potential for leakage behind the drywall at the bottom of every cavity, to some degree. That connection is not always made tightly. Some nail/screw popping is expected, and there is a potential for air leakage. Some measurements made by studies at Forintek on that type of connection might be a source of information for flow coefficients (Onysko, 1993). Normally however, that would not be a desirable construct because of the danger of reverse flow leading to the collection of moisture in walls.

However, to assess the viability of relying on leakage of this nature to dry wet walls, it would be necessary first to assess the drying of walls with vented cavities when exposed to real weather conditions. Those effects might overwhelm any potential benefits from incidental leakage at defects, or at planned leakage paths, which are uncontrolled as to direction of flow under typical weather conditions.

6. DEFINITION OF TEST WALLS AND CONDITIONS

The test walls proposed for simulation are based on conventional framing using full cavity fibreglass insulation, a structural wood sheathing, building membranes, and stucco or other siding on battens of various thicknesses. The following descriptions identify the materials to be used. They also address matters that affect the performance of test walls and decisions that affect the validity of the computer simulations.

Initial Moisture Content

The initial moisture content (MC) distribution can be specified to be uniform in the studs and wood sheathing. The initial MC for the wood studs, suggested by Hazleden (1997), was 40 per cent, dry weight basis. In part, the choice of this moisture level was influenced by the need to have a high enough moisture content in the wood materials to account for drying that would take place during instrumentation and set-up and before the test could begin.

To overcome this drying problem, a different conditioning procedure was decided on by the EDRA technical team. The moisture was introduced by soaking the partially completed test walls in a water bath with only the framing lumber of the partially completed wall assemblies immersed. Most of the sensors, except those that might be damaged by contact with water, are installed before immersion. This soaking protocol allows the walls to be insulated and closed in comparatively soon after the moisture conditioning is completed. It is also expected that the test walls may be exposed to chamber test conditions soon after this closure.

Thus, for both modelling and test purposes, the initial mean target moisture content of the framing is 30 per cent, with the faces assumed to be at 35 per cent MC and the core of the lumber to be at about 25 per cent MC. The oriented strand board (OSB) or plywood sheathing is not directly

exposed to water contact during conditioning, and the moisture content attained is expected to be in the order of 25 per cent. The actual distribution of moisture in the test walls may be quite different, but this can be evaluated when the walls are being prepared for test. The actual moisture distributions at the beginning of the test can be input for the final analysis of the specific test walls.

The Interior RH and Temperature

An interior steady state condition of 20°C and 40 per cent RH was proposed. There is no need to consider any other condition for steady state testing. The interior RH chosen is not material when air leakage is not involved.

The Exterior RH and Temperature

Originally, the steady state exterior conditions proposed were 5°C and 80 per cent RH. As the rate of drying is slow under these conditions, and because one of the main purposes of the EDRA project is validation of computer programs, other drying conditions may be considered. Additional analytical runs were included at different conditions to assist in planning the final chamber conditions for the test program. These additional conditions are identified in the final parametric analysis outlined in Chapter 9 of this report.

Framing Lumber

Originally, the CMHC plan called for 2 x 6 (38 x 140 mm) nominal dimension lumber framing at 400-mm spacing. This converts to a spacing of 15.75 inches. Certain portions of the WALLDRY code are set up internally assuming a 406-mm (16-inch) stud spacing. Any other spacing requires an alteration in that code. Currently, the number of effective studs (as a source of moisture) is provided as input to the program. Single top and

bottom plates are assumed, with only drying to the inside of the wall cavity permitted. In other words, the test wall width is assumed to be part of a wider wall, and edge effects are assumed to be the same as for the test portion. In fact, by having a typical stud at both edges, the assumed boundary conditions are not fully met for narrow walls.

The more recently proposed CMHC plan incorporated into the EDRA proposal for implementation by Forintek Canada Corp. involves use of nominal 2 x 4 (38 x 89 mm) framing recognizing that, for experimental purposes, this provides a smaller interior moisture load and a higher thermal loss. Both conditions speed drying.

In order for the simulations to provide information that would be useful to guide the experimental work, the simulations are performed using 2 x 4 (38 x 89 mm) framing. To show the influence of greater wall cavity insulation and moisture storage, a selected number of simulations are done using 2 x 6 (38 x 140 mm) framing.

Insulation

Fibreglass insulation is assumed with full cavity installation. The effect of greater stud depth (and more insulation) demonstrates the influence of a lower heat loss on drying performance.

Double Plates Top and Bottom

For purposes of the wall drying experiment, double top and bottom plates have been proposed. However, WALLDRY assumes that only single top and bottom plates are involved for exposure to the wall interior cavities. WALLDRY does not have the ability to study the detailed moisture distribution within the framing, whether single or double plates. The second top and bottom plates should be isolated from the others they are in contact with so they do not act as sinks or sources of moisture. Also, to have the side boundary conditions mimic those for wider walls, moisture ingress into the edge studs (during wetting of the walls for the experiment) should only be allowed through the sides of the lumber facing the inner wall cavities.

The use of double top and bottom plates is associated with the practice used in apartments where concrete topping is placed over the subfloor. The detail involving this application would have the concrete topping in contact with the lowest plate, a condition that is not being simulated in this study. Consequently, for best comparison between test measurements and predictions by WALLDRY, only one top and bottom plate should be provided as a source (and sink) for the wall cavities. Any additional framing required to make the wall sturdier for handling should, therefore, be isolated from the test frame, if possible. Since drying of the outermost bottom and top plates will be slow, it is possible that their effect on drying rates will not be large, and this concern may not end up being significant.

Interior Wall Facing

A 6-mil polyethylene vapour barrier is assumed in combination with the interior wall finish of 12-mm gypsum drywall. The actual inside faces of the walls for the test program are Crezon plywood painted to isolate it from moisture exchange with the "indoor" conditions. These indoor conditions are not expected to vary significantly. Use of this plywood was planned to strengthen the wall for handling to prevent cracking of the stucco finish. This face layer is installed with screws to be easily removed for examination of the interior wall cavities and for re-wetting of the test wall, if needed.

Since the inner face layer is not coupled to the moisture movement in the wall, and the thermal properties are not that dissimilar from gypsum board, the computer simulations are done assuming the wall liner is gypsum board. One series of simulations involves removing the polyethylene vapour barrier to permit moisture movement from the wall to the indoor air to examine the difference in the drying rates obtained. That test is not currently planned for the laboratory program, but the simulation is being provided to answer some questions that have arisen concerning that practice.

Exterior Sheathing: 12.5-mm OSB

The EDRA project team selected the specific manufacture of OSB and plywood materials for the test program. All panels used are derived from one lift of material to try to minimize the variation in properties. As the particular properties corresponding to the material chosen are not known at this time, the available properties for OSB from the literature are assumed. This parametric study proposes to examine drying conditions using OSB sheathing in the main. The drying of walls with plywood sheathing is examined as a separate question, as walls of this type are included in the test program.

Sheathing Paper and Sheathing Membranes

For this parametric study, a commonly used building membrane consisting of two layers of overlapping "30-minute" building paper is assumed. However, another commonly used sheathing membrane is also used in the EDRA project: a spun-bonded polyolefin (SBPO) material designed to meet the requirements of standards in Canada. This material conforms to the Canadian Construction Materials Centre (CCMC) technical requirements for air barrier systems for exterior walls of low-rise buildings. The properties for both of these materials are reasonably well characterized. They have been included in the database for the computer model.

Spacing of Batten Strips

The typical practice for spacing batten strips in reconstruction of exterior walls has been to attach the batten strips directly opposite the wall studs for good anchorage. As well, intermediate to these battens, additional battens are sometimes installed directly to the structural sheathing. In part, this is done to reduce billowing of the sheathing membrane material. They also provide better support for the stucco. These intermediate batten strips reduce the area of wall sheathing available for diffusion of moisture out of the wall cavities. For this parametric study and the EDRA project,

the batten strips used are assumed to be applied only opposite the wall stud locations and to be of a width that does not inhibit the movement of moisture through the sheathing. In practice, wood-based batten strips absorb and desorb moisture, but these effects are not modelled here.

Continuous Weighing and Moisture Loss Mechanisms

The experimental design for the test program calls for continuous monitoring of the total wall weight. In order for the total predicted wall weight to be available for comparison, several different weight change calculations were incorporated into the model. Since there could be moisture loss through the stucco, as well as moisture lost by ventilation of air through the space provided, and potential drainage from the wall, these additional total moisture change mechanisms were calculated on an hourly basis. For the case that involves removal of the polyethylene vapour barrier, moisture lost or gained to the indoor air is also tallied. Redistribution of moisture from the wall to the outer layers as condensed water films held on the faces of materials, and those that drain to the bottom of the wall are also tallied separately, if conditions lead to their formation.

Stucco

The thickness of stucco is assumed to be 21 mm. Several conditions were considered.

- (A) When the variables consist only of ventilation parameters, so the moisture lost only through ventilation is evaluated, the properties of the stucco were chosen to be very resistant to absorption or desorption of moisture. Essentially, the stucco was decoupled from the moisture balance. This provides some information on the maximum benefit that the ventilation cavities alone can provide. This represents a lower bound estimate of drying when moisture-resistant stucco and a relatively impermeable backing are used.

- (B) When the stucco is applied directly against the building paper, two layers of building paper are assumed. The stucco is modelled as three layers of material, this being the number of layers that have been assumed for cladding within the WALLDRY program.
- (C) When the stucco is applied to batten strips with an expanded metal lath as reinforcement, the inner layer involving that reinforcement may be less able to pass moisture to the interior of the stucco. There is, as yet, no data to support this assumption. Since the stucco is forced into the mesh and partly into the ventilation space, the surface area of the exposed stucco available for absorption is increased. In the absence of any test data for this case, and for these parametric runs, it is assumed that the same properties hold for the back face layer as in case B. If the face and back treatments for the stucco are different, the thickness and properties for each layer can be specified individually.

The hygroscopic behaviour of a stucco clad wall will depend on the properties of the backing and the finishes provided on the outer face of the stucco. The moisture balance in the ventilation cavity is governed by the absorption/desorption of moisture into and out of the two faces of the ventilation cavity, and the rate at which moisture can be expelled by ventilation driven by thermal buoyancy and other air exchange effects in the ventilation space. The airflow depends on the airflow characteristics of the inlet and outlet vents and the resistance to flow in the ventilation space itself. Consequently, for cases when the stucco is not decoupled from the wall, it is necessary to output all the hourly mass flow rates to determine what moisture is being redistributed and stored as opposed to that being lost from the wall by ventilation and diffusion of water vapour.

Neutral Pressure Test

This study concentrates on the behaviour of the walls with a neutral pressure (i.e., no intentionally applied pressure difference between the "indoor" and "outdoor" conditions are investigated). The

polyethylene vapour barrier and the inner lining of the test walls, together with the edge sealing of the individual wall boundaries guarantee that no air leakage can occur through the wall cavities. Thus, even if the mechanical control system for the chamber cannot be precisely controlled, no through-wall airflow takes place.

Should infiltration or exfiltration of air ever be considered for study, the amount of airflow through the test wall will be controlled by the air permeability of the outer wall, and the size of openings provided through the inner wall liner. Since this cannot be predicted at this time, except for such defects as are created by unsealed electrical outlets, no simulations are included to illustrate these effects.

Wind Pressure Differentials

As noted earlier, the computer program was adapted to allow for simulation of a specific wind pressure distribution on the outer face of the test walls. Both the simulated wind speed and wind direction were added as input parameters in the laboratory weather file. For comparison of the performance of test walls with real laboratory conditions or with real exterior test conditions, the pressure differentials between the top and bottom of the walls need to be monitored.

In summary, the above discussion on each of the relevant characteristic for both the makeup and testing of walls for study includes part of the decision-making process that led to modifications in the EDRA study. Additionally, the discussion identified decisions that limited the scope of the parametric study. The next chapter deals with how the properties of the ventilation space are characterized. The features of the basic wall system investigated are:

- 12.5 mm gypsum;
- 6-mil polyethylene vapour barrier;
- 2 x 4 (38 x 89 mm) framing lumber at 406-mm spacing;
- fibreglass insulation;
- 12.5-mm OSB sheathing;

- two layers of 30-minute building paper;
- ventilated cavity (ranging from 1 mm to 38 mm with various gap openings);
- 21-mm stucco (coupled and decoupled);
- indoor conditions (40 per cent RH 20°C);
- exterior conditions (various RH and temperature conditions); and
- neutral pressure conditions.

Deviations from this basic wall are identified when several additional questions are studied. The total wall area assumed for the simulations is the overall area (2.98 m² ~ 3 m²). Drying rates noted in much of this report are reported in kg/m²/week. Moisture flow through the contact between the sheathing and the framing was not modelled.

7. AIR LEAKAGE CHARACTERISTICS

The rate at which test walls in the experimental design can dry to the outside (to the chamber conditions) is largely controlled by the rate at which moisture can diffuse into the outer ventilation cavity and be dissipated to the outside by air exchange with the outside air. This exchange is controlled by thermal buoyancy effects and by airflow in that cavity, as well as by restriction to flow provided by the flashing details at the top and bottom of the cavity. As this is critical to the parametric study, and the airflow properties are part of the input file for WALLDRY, the approach taken to define the airflow properties is examined.

Air Cavity Flow Characteristics

Determining an expression for resistance to airflow in an air cavity can be based on experimental work by Hopkins and Hansford (1974) and by Etheridge (1977). The following equation was derived for a straight-through gap on the basis of experimental data (Hopkins and Hansford, 1974).

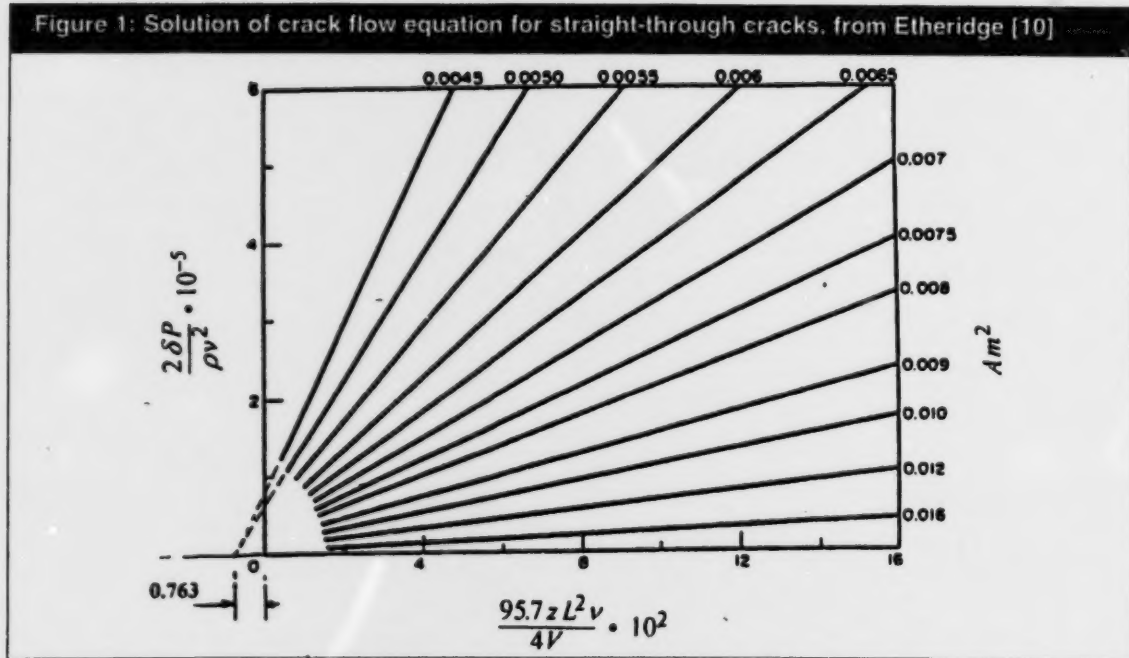
$$1/C_z^2 = 95.7 (z/d_h \cdot 1/R_{ey}) + 1.50 \quad [1]$$

where:

C_z^2	=	discharge coefficient
z	=	depth of crack
d_h	=	$4A/(\text{wetted perimeter}) = 2y$
A	=	area of crack
y	=	thickness of crack
R_{ey}	=	Reynolds number

Etheridge (1977) rewrote the above expression in a form of a cubic equation involving the area of the crack (A) and its other known properties, including air leakage test information. His solution to the equation is shown in Figure 1.

Onysko and Jones (1988) noted that the series of lines for each value of crack area in Figure 1 radiate from a near common point on the horizontal axis (at a value taken to be 0.763 for the straight-through gap solution). Since crack flow areas for siding and small gap widths are



relatively small, this common point was chosen to bias the location of the "centre" from which the lines appear to radiate to favour modelling of smaller gap areas. When gaps are relatively large, the error in representing airflow, particularly under low differential pressures, is less critical.

The ratio of the vertical to horizontal components of each radiating line in Figure 1 becomes the tangent of the angle in terms of the units on each axis. For the straight-through joint, the evaluation of the tangent (r) can be obtained from the following equation.

$$r = \frac{\frac{2 \delta P \cdot 10^{-5}}{\rho V^2}}{\frac{95.7 Z b^2 \mu}{4 V} \cdot 100 + 0.763} \quad [2]$$

where:

δP = pressure difference (N m⁻²/Pa)

ρ = density of air = 1.2 Kg/m³

V = volumetric flow in m³/s

Z = joint depth in metres

b = joint length in metres

μ = kinematic viscosity of air = 15.7935 • 10⁻⁶ m²/s.

Onysko and Jones (1988) correlated the above expression and other expressions for r for single bend and double bend gaps, with the gap area ($A = y \cdot b$) to obtain the following relationship:

$$A = 0.00458 \cdot r^{-0.352} \quad [3]$$

Thus, given known information about the gap and the results of a leakage test, substitution leads directly to computation of the effective gap area, and the effective gap thickness. In practice, some types of gaps can only be evaluated by test because of surface roughness and variable dimensions. Alternatively, given information about the geometry of a hypothetical smooth surfaced gap, including its length, thickness and depth, the airflow characteristics through it can be determined.

Now, rearranging equation [3] and substituting equation [2] for r , the expression can be put into a

form that allows the coefficients for the airflow relationship to be input to WALLDRY in the form for which it was designed. That form is:

$$\delta P = K_1 Q + K_2 Q^2 \quad [4]$$

Defining Q = litres/min/m, $V = Q/60,000$, the following expression results for the air gap y (in metres) behind the cladding for an element height having a width of b metres:

$$\delta P = \frac{8.5517}{10^9} \frac{Z b^2}{(yb)^{2.8409}} Q + \frac{2.877781}{10^{12}} \frac{1}{(yb)^{2.8409}} Q^2 \quad [5]$$

The first term represents laminar flow while the second term represents turbulent flow related to entry of air at the entrance to the cavity. It is likely that the air cavity we are attempting to model will only have restrictions and bends at the top and bottom, while within the air space itself, flow will be relatively laminar and dominated by the first term. It is considered appropriate to use the first term to describe the flow characteristics of the cavity space for each vertical element in the wall, and to assign other properties for the closure at the top and bottom.

Burnett and Straube (1995) presented the laminar airflow in the cavity by the following expression:

$$\delta P = \frac{Z q}{4610 \gamma b y^3} \quad [6]$$

Where, γ is a blockage factor for cavities in masonry walls, and q is the airflow in m³/s. In this study, γ will be taken as unity. If there are obstructions related to the characteristics of particular types of spacers, or by the surface characteristics of the materials facing the ventilation cavity, the coefficients will have to be evaluated experimentally as these characteristics may introduce turbulent flow throughout the wall height.

As a check on these two expressions, setting $q = Q = 500$ L/min = 0.00833 m³/s, $b = 1$ m, $y = 0.0048$ m, and $Z = 1$ m, the value of the first term in the equation [4] is 16.53 Pa, while the value of equation [5] is 16.34 Pa. The relative values diverge above and below this because of the difference between the exponents between the

two expressions. Laminar airflow in cavities of stucco walls with closely spaced batten strips may be more appropriately modelled using expression [4] because of the non-linear influence of the cavity width b as the spacing between batten strips becomes narrower.

Air Leakage Characteristics Through Top and Bottom Vents

Modelling the flow characteristics of the top and bottom partial closures to the air cavity may be done using expressions derived from Etheridge for single bend and double bend gaps that parallel equation [4]. However, it is simpler to use equations based on design experience in Europe that was summarized by Burnett and Straube (1995). This also simplifies specification of the parametric cases to be addressed in this investigation.

The differential pressure (δP) across flashing drip edge opening at the top and the bottom of the air cavity can be expressed as:

$$\delta P = 0.6 \varepsilon \left(\frac{q}{by} \right) \quad [7]$$

where ε = 0.5 for straight entry into a cavity
 = 0.88 for straight exit from a cavity
 = $0.885 (b_1/b_0)^{-0.86}$ for a rectangular elbow ($b_0 < b_1$)

and b_0 = entry slot depth
 b_1 = cavity depth = y

Thus, the model for the pressure difference across the bottom flashing detail for entry of air into the bottom of the air cavity is taken to be the sum of the entry and rectangular elbow coefficients into the air cavity (for a unit width of wall, $b = 1$):

$$\delta P = 0.6 \left[0.5 + 0.885 \left(\frac{b_1}{b_0} \right)^{-0.86} \right] \left(\frac{Q}{60,000 b b_0} \right)^2 = \frac{0.5 + 0.885 \left(\frac{y}{b_0} \right)^{-0.86}}{6 \cdot 10^9 b_0^2} Q^2 \quad [8]$$

For a unit length of flashing at the top of the wall, the corresponding expression can be taken as:

$$\delta P = 0.6 \left[0.88 + 0.885 (b_1 b_0)^{-0.86} \right] \left(\frac{Q}{60,000 b b_0} \right)^2 = \frac{0.88 + 0.885 \left(\frac{y}{b_0} \right)^{-0.86}}{6 \cdot 10^9 b_0^2} Q^2 \quad [9]$$

Laminar flow from the air cavity to the rectangular bend at the top of the wall does not involve an entrance coefficient, so only the elbow and exit coefficients need to be used. In practice, under wind exposure, one cannot predict if air will come in or out of a flashing detail, but the assumption that air will enter at the bottom and exit at the top is assumed to hold more frequently. The use of Q having units of L/min is retained for these equations because those are the units for the coefficients K_1 and K_2 currently expected by WALLDRY. Internal to the program, the coefficients are modified so flow is determined in m^3/s . It was decided to leave the current computer code in that state, in part because testing of joints and the flow coefficients will likely be done in those units (L/min). This was also done to permit existing input data files to continue to be used with the modified program.

It is noted that expressions [8] and [9] provide only the K_2 coefficients for turbulent flow for the entry and exit flashing for the air cavity. The K_1 coefficients for these joints can be set to zero without involving a zero-divide error. For longitudinal slits or gaps, some laminar flow may be expected and K_1 is likely non-zero. Consequently, as a gesture in that direction, K_1 was made equal to K_2 , which resulted in only a very minor change in moisture loss by venting (< 0.04 per cent).

With regard to the characteristics of the ventilation cavity, it will likely behave as a full-height single cavity. For analysis, it is treated as nine separate equal vertical elements with the laminar flow coefficient specified for each element of height Z .

The actual flow restrictions depend on the specific flashing design chosen, and this can only be determined by test for final designs. Defining

these flow coefficients more accurately is not particularly critical for this parametric analysis. This matter should, however, be considered in the experimental plan for the practical ventilation slots incorporated in the construction of test walls.

The air cavity depth varied from 1 mm to 38 mm according to the matrix of test runs shown in Table 2. The wall height is assumed to be 2.44 m divided into nine elements each 0.2667 m high. The coefficients for the bottom entry to the air cavity, the top exit from the air cavity and the laminar flow coefficient for each vertical element are provided in tables 3 and 4, based on the above equations. Allowing the b_0 values to take on the same range as the cavity depths simplifies the specification of the flow coefficients for the various restrictions instead of specifying the gap heights as a percentage of wall area.

Finally, the stucco cladding, although it may eventually contain cracks and permit some airflow between the ventilation space and the outdoor air, is treated as a continuous barrier. The horizontal joints between vertical elements in the WALLDRY formulation become virtual joints. Specification of the flow coefficients for these intermediate virtual gaps cannot be set to zero because the iterative solution for airflow would involve division by zero. Instead, the coefficients for these gaps were set to a sufficiently large number so that in the solution, the virtual flow through these joints was at least 10^6 smaller than the flow through the actual gaps at the top and bottom of the ventilation cavity. A typical input file for one of the walls in this series is provided in Appendix A, and a typical truncated input weather file is provided in Appendix B.

Table 2: Ventilation cavity depth/vert gap height set (21 combinations)

Vent Gap Height (mm)	Venting Cavity Depth (mm)					
	38	19	12	5	2.5	1
1	*	*	*	*	*	*
2.5	*	*	*	*	*	N/A
5.0	*	*	*	*	N/A	N/A
12.0	*	*	*	N/A	N/A	N/A
19.0	*	*	N/A	N/A	N/A	N/A
38.0	*	N/A	N/A	N/A	N/A	N/A

Note:

N/A signifies that the combination was considered not applicable.

Table 3: Flow coefficient K_2 for ventilation gaps formed by the top and bottom flashing for a 1-m length of gap [$\text{Pa}/((\text{L}/\text{min})/\text{m})^2$]

Gap Height (m)	Depth of Ventilation Cavity (m)					
	0.038	0.019	0.012	0.005	0.0025	0.001
Bottom flashing						
0.0010	8.9793E-05	9.5057E-05	1.0074E-04	1.2029E-04	1.5041E-04	2.3083E-04
0.0025	1.5806E-05	1.7458E-05	1.9457E-05	2.6336E-05	3.6933E-05	
0.0050	4.3646E-06	5.2050E-06	6.1122E-06	9.2333E-06		
0.0120	9.5882E-07	1.2686E-06	1.6030E-06			
0.0190	4.5595E-07	6.3943E-07				
0.0380	1.5986E-07					
Top flashing						
0.0010	1.5313E-04	1.5839E-04	1.6407E-04	1.8362E-04	2.1374E-04	2.9417E-04
0.0025	2.5739E-05	2.7592E-05	2.9591E-05	3.6469E-05	4.7067E-05	
0.0050	6.8979E-06	7.7384E-06	8.6456E-06	1.1767E-05		
0.0120	1.3986E-06	1.7084E-06	2.0428E-06			
0.0190	6.3139E-07	8.1487E-07				
0.0380	2.0372E-07					

Table 4: Flow coefficients K_1 and K_2 for the ventilation cavity element height = 0.26667 m element width = 1 m

Ventilation Cavity Depth y (m)	K_1 $\text{Pa}/(\text{L}/\text{min})/\text{m}$	K_2 $\text{Pa}/((\text{L}/\text{min})/\text{m})^2$
0.0010	7.5984E-01	9.5897E-04
0.0025	5.6262E-02	7.1007E-05
0.0050	7.8527E-03	9.9106E-06
0.0120	6.5294E-04	8.2406E-07
0.0190	1.7697E-04	2.2335E-07
0.0380	2.4701E-05	3.1174E-08

8. MATERIAL PROPERTIES

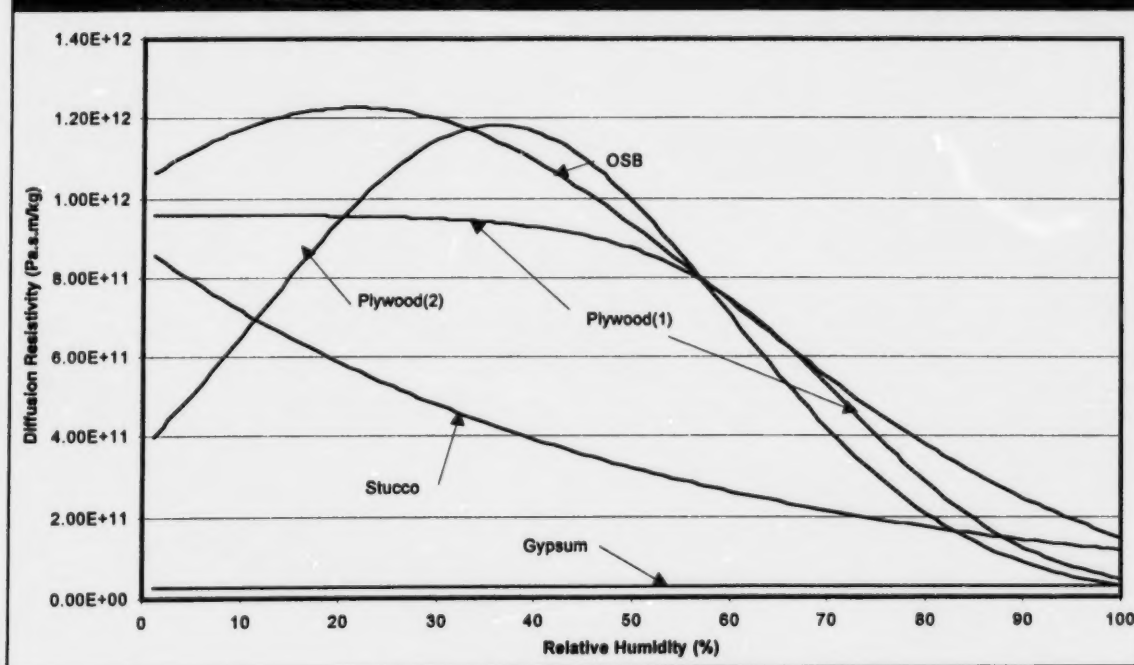
Documenting the changes to WALLDRY is beyond the scope of this report. The material properties currently in the fixed database are found in Appendix C. For materials, whose diffusive properties are affected by the moisture content, some data available in the literature were fitted with expressions, and the algorithms were incorporated into the program. Some other properties were secured by discussion with researchers at the IRC. In this chapter, only a few of the resulting relationships used for analysis in this report are described for the record. A plot of the diffusion resistivity (the inverse of vapour permeability) for some materials is provided in Figure 2.

There are few consistent properties available for most of the construction materials available on the market. The properties for plywood were obtained from McLean et al. (1990). The source of the material was an exterior grade plywood made of

five plies of Malaysian Morrant wood. This is shown plotted in Figure 2 as the curve for Plywood(1). Another relationship for plywood was extracted from MOIST Release 2.0 (Burch and Thomas 1993, as referred to in McLean et al., 1990). This relationship is shown plotted in Figure 2 as Plywood(2). The lower diffusion resistivity for low RH values is not valid for Plywood(2) but is merely an artifact of the equation from that reference which was curve-fitted to vapour permeability data.

The vapour permeability relationship for the OSB was obtained from Burch and Thomas (1993). The inverse is also shown plotted in Figure 2. Again, due to the form of the fitted relationship in the range of valid data, there is a hump in the diffusion resistivity plot that is not valid below about 40 per cent RH. More recently, work at the IRC on a range of commercial OSB panels has

Figure 2: Diffusion resistivity as a function of relative humidity for several materials implemented in WALLDRY



been completed, but the results were not available in time for this parametric study.

For stucco materials, again, there is a lack of data. The relationship shown plotted in Figure 2 was obtained by the writer by fitting a logarithmic relationship to some test data provided by the IRC. The scatter of permeability data for any one type (or source) of stucco varied considerably. The relationship shown was obtained by ignoring very high permeability results. In effect, this plot passed through the mean of the higher resistance material and, as such, represents a conservative relationship for the case when moisture retained is on the inside of the wall.

One value for the diffusion resistivity for gypsum board (1.5748×10^{10} Pa.s.m/kg) is to be found in Burch and Thomas (1993). Other values in the literature, for example Galbraith and McLean (1990), include 3.06×10^{10} Pa.s.m/kg, which is

somewhat greater but is still quite low compared with other building materials. Since the resistance to vapour flow is further enhanced by the paint employed to finish the gypsum board, it was considered sufficient to settle on one value as an example. In this case, the 3.06×10^{10} Pa.s.m/kg value was selected for illustrative purposes.

For spun-bonded polyolefin, a fixed value of 4.44×10^{12} Pa.s.m/kg was taken across all RH conditions based on a permeance of $1,500$ ng/Pa.s.m² and an assumed thickness of 0.00015 m. For 30-minute building paper, a value of 4.76×10^{12} Pa.s.m/kg was used for relative humidity under 50 per cent. For values between 50 per cent and 100 per cent RH, the value was assumed to decrease linearly from the above value to a low of 3.45×10^{12} Pa.s.m/kg. This was based on permeance testing of building paper assumed to be 0.0005 m thick.

9. REVISED PARAMETRIC PLAN

In light of the discussion in the previous chapters, this parametric analysis is structured around specific questions, which fall out of the stated objectives, and from the discussion on choices made for the construction of the walls.

If all variables were studied in equal measure, a very large number of simulations would be required. Early runs showed that under some specific circumstances, steady-state moisture removal conditions were quickly established. It was then logical to consider comparing the walls on the basis of relative rates of moisture loss as a function of venting characteristics, rather than attempt to determine how long it would take each wall to dry to a "safe" moisture level. The initial moisture conditions are somewhat arbitrary to begin with, and drying time, while useful in the abstract, is no more than an indication of relative drying rates. The difference in time to run a one-week simulation vs. a five-month simulation was significant, particularly since the essential results were similar. These short simulations were used primarily to permit a larger number of simulations to be done to answer the questions posed. Fewer five-month runs were also done to demonstrate the rate at which moisture was lost from different elements.

In short, the primary combinations of ventilation gaps and cavity depths used for the main questions posed for this parametric analysis involved 21 combinations. The vents at the top and bottom were made equal in dimension for most of the simulations to allow the maximum degree of ventilation possible. In reality, there are drawbacks to permitting too large an air exchange in the ventilation cavity. It is normal, under current practice, to provide a sizable ventilation/drainage vent at the bottom of the ventilation space, and to have an essentially closed air column at the top. That possibility is also addressed in this study. The 21 combinations of venting space and ventilation gap size are shown in Table 2.

Question #1: What is the influence of the ventilation cavity depth and the ventilation gap dimensions – decoupled stucco?

The stucco was decoupled from the wall performance in order that moisture could only depart from a wall by air movement through the ventilation cavity and its top and bottom gaps. The stucco was decoupled by specifying that it be impermeable to moisture flow (i.e., no moisture was permitted to be absorbed or transmitted through the stucco). The thermal properties were left unchanged. The initial hours of a simulation are affected by the specification of the initial moisture content of the various materials, including the gypsum board that is essentially not involved in the moisture flow out of the wall, but is involved in the total mass of the wall. To avoid including this initial redistribution and acclimatization period, drying during the first day was ignored in calculating the initial weekly drying rate. The short simulation runs were for eight days of drying. The chamber conditions chosen were 5°C/70 per cent RH.

Question #2: What is the influence of chamber RH on the drying rates - decoupled stucco?

The current relative humidity for the chamber conditions representing the outdoor conditions chosen by the EDRA team is 70 per cent. However, some have suggested that a faster drying rate would be achieved by using lower RH conditions in the chamber without invalidating the purpose of the experiment for both investigating the ability of a wall to dry, and to provide results for validation of computer models. Consequently, simulations of the type described above were also done for 50, 60 and 80 per cent RH. Essentially, the set of runs for Question #1 and these runs form a comparison set in which the RH conditions are varied from 50 to 80 per cent. A total of 84 simulations were required.

Question #3: What is the influence of chamber temperature on the drying rates – decoupled stucco?

Choosing a different chamber temperature affects the thermal drive across a wall which reduces the vapour pressure difference while at the same time increasing the ability of the air in the chamber to take on and remove moisture from the wall by ventilation through the ventilation cavity. However, lower thermal differentials between the "indoor" and "outdoor" air reduce the thermal buoyancy of the air in the ventilation cavity which, in turn, reduces its rate of flow. This question was answered by retaining the relative humidity in the chamber at 50 per cent and allowing the temperature in the chamber to range from 5°C to 20°C in 5°C increments. This required 63 additional eight-day simulations.

Question #4: What is the influence of chamber RH on the drying rates of walls with coupled stucco cladding? How much moisture leaves by diffusion compared to venting?

These questions parallel the question related to decoupled stucco. They have relevance as to whether the total moisture loss can be measured sufficiently well by weighting walls. The information is also relevant to assess how coupled walls dry, particularly when there is no ventilation possible. To provide some insight into these questions required 84 additional eight-day simulations to parallel the information provided for the decoupled stucco cases.

Question #5: What difficulties will be experienced in separating actual moisture loss from the wood elements in the wall from redistribution of moisture during experiments on drying?

While total mass changes of a wall during a drying study can be obtained accurately experimentally, the question remains as to what magnitude of error results in inferring wall drying using this information. This question is probed by examining the results of a limited number of simulations.

Question #6: What are the moisture loss distributions in the walls, and the moisture gradients in different elements of the walls?

To provide an answer to this for all the test parameters would be an onerous task. Instead, a

specific wall was selected to illustrate the manner in which moisture is redistributed and lost when the wall has coupled stucco. That wall case will be S19-12 (19-mm ventilation cavity, 12-mm vent gaps, top and bottom).

Question #7: What are the moisture loss distributions in walls when the ventilation gap at the top is closed?

It is typical practice to not ventilate deliberately the top of a ventilation space behind stucco cladding. What results is a stagnant column of air that permits ready drainage to the base opening, but discourages ventilation. At the same time, it is not believed that such a cavity is fully blocked. Mismatch between materials, joints in the furring, cracks in the stucco, even nail popping of the fasteners holding the stucco lath to the furring strips may permit the formation of a small air leak. For illustration, the effect of allowing some flow from a minimal gap (1 mm) is demonstrated.

Question #8: What effect does a simulated wind have on drying rates?

As noted in Chapter 4, the WALLDRY program was modified to accept a specific wind speed (1.5 m/s) and direction and with a specific variation of wind pressure coefficients. One specific basic wall case examined was S19-05 (19-mm ventilation cavity depth, 5 mm top and bottom ventilation gap heights). Five-month simulations were run, both with and without the wind pressure applied against the bottom vent gap. The chamber conditions were intentionally chosen to be more beneficial for drying 5°C and 50 per cent RH instead of 70 per cent RH to accentuate the change.

Question #9: What is the difference in drying rates when plywood is used instead of OSB, using the properties implemented in WALLDRY?

As illustration, for this examination, the example wall chosen is the same test wall (S19-12) examined for Question 6, and the chamber conditions are 5°C and 70 per cent RH. A five-month simulation is used.

Questions #10: What is the effect of using 2 x 6 framing instead of 2 x 4 material?

While this appears to be a valid question, the comparison is deceptive. While the greater depth of framing leads to cooler outer wall elements, the initial conditions specified imply that the same distribution of moisture would pertain as for the 2 x 4 (38 x 89 mm) framed walls. However, this also means that because the framing is deeper, there is 57 per cent more material, and 57 per cent more moisture to be dissipated for the same initial assumed moisture contents in the shell and core of the framing material. Given these qualifications, the comparison is not likely to be useful except for the fact that far greater moisture levels will be held for a longer period of time. None of the simulations for drying were extended to the point that "safe" conditions pertain in any case.

Question #11: What are the drying rates when the polyethylene vapour barrier is not installed?

There have been suggestions that walls dry out slowly because vapour barriers are used. This parametric study does not intend to weigh into the controversy about when a polyethylene vapour barrier is required, only to provide one example of this situation when it is not installed. To assist in assessing this case, a worst case situation was selected, which could be compared with previous runs. That case involves a fully closed top vent and test wall S19-12. A far worse case is when the stucco is installed directly against the sheathing paper and against the wall. However, as an example, this case is sufficient to describe order of magnitude effects.

Question #12: What is the drying performance of two reference walls, built using vinyl siding and wood siding subject to the same moisture load as used in this parametric study?

The input files used for these examinations were prepared in the 1980s. The air leakage characteristics through the vinyl siding, the wood siding joints and for the cavity behind the siding were as determined experimentally in bench-top tests at that time. No changes were made to this information. However, all the other materials were chosen to parallel that for the walls with stucco siding. Only the equivalent of one layer of building paper was assumed.

10. RESULTS

Decoupled Stucco Walls

Decoupling the stucco from the moisture performance of the wall served two purposes. One concerned the desire to have relatively short simulations. The second reason was to provide a lower bound solution, which represents the actual situation for some real and proposed stucco cladding systems.

Questions #1 and #2: What is the influence of the ventilation space and the ventilation gap dimensions on the drying rate as a function of chamber RH conditions?

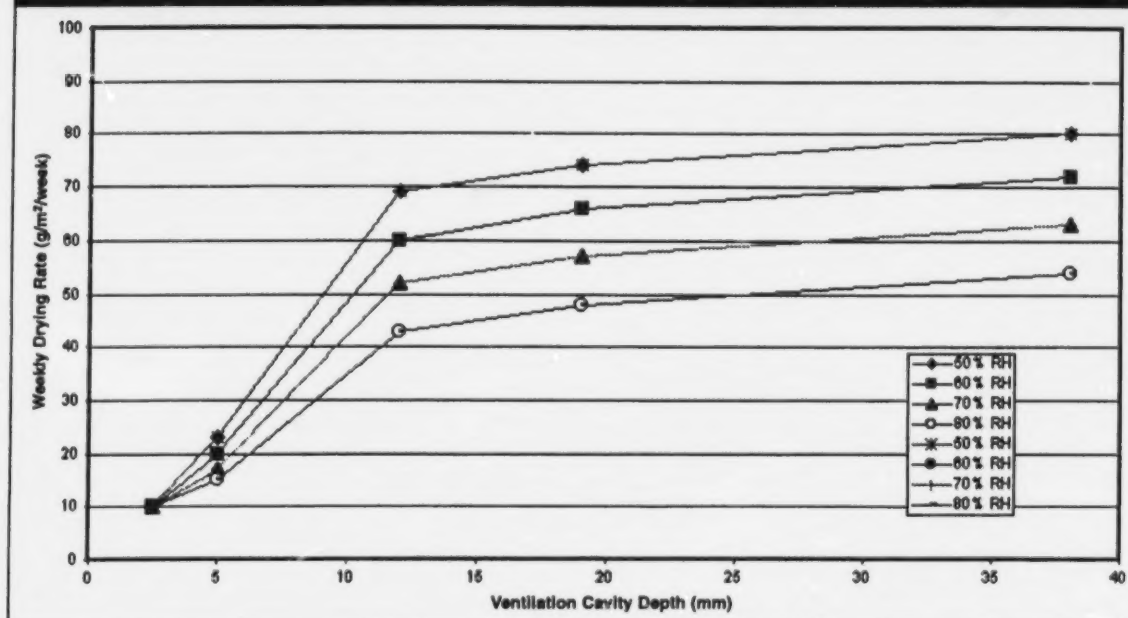
The results for the 84 simulations to answer this question are provided in Table 5. There, the initial weekly drying rates are summarized for all combinations of venting space/gaps and for each of four different chamber RH conditions ranging from 50 to 80 per cent.

The salient observations concerning Table 5 are that the variation on drying rate is more dependent on ventilation cavity depth, than it is on the ventilation gap height. There are subtle differences in temperature gradients in the air column. These drive buoyancy and the ability to pick up moisture from the inner wall. However, the net effect is clear. Also, the effect of chamber RH is also clear. The lower the RH, the greater the ability of the air to pick up moisture in the cavity and to speed drying. The 50 per cent RH case results in drying that is approximately 30 per cent more rapid than the 70 per cent RH case. For a specific case involving a 19-mm ventilation space and 12-mm ventilation gaps at the top and bottom (S19-12), the relative drying rate over the range 80/70/60/50 per cent RH, using the 80 per cent case as the reference, results in ratios of 1.0/1.20/1.39/1.57.

Table 5: Effect of ventilation parameters and chamber RH on the weekly drying rate (g/m²/week) neutral pressure, decoupled stucco, chamber temperature 5 C

Vent Gap Height (mm)	Ventilation Cavity Depth (mm)						Ventilation Cavity Depth (mm)					
	38	19	12	5	2.5	1	38	19	12	5	2.5	1
Chamber RH = 50%												
1	78	70	67	25	10	10	70	61	59	22	10	10
2.5	80	74	69	23	9	N/A	72	66	60	20	10	N/A
5	84	76	72	25	N/A	N/A	75	67	64	22	N/A	N/A
12	84	77	73	N/A	N/A	N/A	74	68	64	N/A	N/A	N/A
19	82	77	N/A	N/A	N/A	N/A	73	68	N/A	N/A	N/A	N/A
38	80	N/A	N/A	N/A	N/A	N/A	71	N/A	N/A	N/A	N/A	N/A
Chamber RH = 70%												
1	61	53	51	19	10	10	53	44	43	18	10	10
2.5	63	57	52	17	10	N/A	54	48	43	15	10	N/A
5	66	58	55	19	N/A	N/A	57	49	46	16	N/A	N/A
12	65	59	55	N/A	N/A	N/A	55	49	46	N/A	N/A	N/A
19	64	59	N/A	N/A	N/A	N/A	55	49	N/A	N/A	N/A	N/A
38	61	N/A	N/A	N/A	N/A	N/A	52	N/A	N/A	N/A	N/A	N/A
Chamber RH = 60%												
1	70	61	59	22	10	10	70	61	59	22	10	10
2.5	72	66	60	20	10	N/A	72	66	60	20	10	N/A
5	75	67	64	22	N/A	N/A	75	67	64	22	N/A	N/A
12	74	68	64	N/A	N/A	N/A	74	68	64	N/A	N/A	N/A
19	73	68	N/A	N/A	N/A	N/A	73	68	N/A	N/A	N/A	N/A
38	71	N/A	N/A	N/A	N/A	N/A	71	N/A	N/A	N/A	N/A	N/A

Figure 3: The effect of RH conditions in the chamber on the weekly drying rates as a function of the ventilation cavity depth for a vent gap size of 2.5 mm - decoupled stucco, $T = 5^{\circ}\text{C}$



Concerning the influence of ventilation spaces 5 mm and under in depth, the drying rate is relatively slower than when that space is increased to 12 mm or higher. This is shown in Figure 3, where, for a specific ventilation gap size of 2.5 mm, the effect of the ventilation space is readily apparent as a function of the space between the wall and the back of the stucco.

Questions #1 and #3: What is the influence of the ventilation space and the ventilation gap dimensions on the drying rates as a function of chamber temperature?

The results for 84 simulations to answer this question are provided in Table 6. There, the initial weekly drying rates are summarized for all combinations of venting space/gaps, and for each of four different chamber temperature conditions ranging from 5°C to 20°C in 5°C increments. For this comparison, the RH in the chamber was held at 50 per cent RH.

In Table 6, it is again seen that the ventilation cavity depth was more important than the vent gap sizes. Increasing the temperature of the chamber while holding the relative humidity at a

low level increased the weekly drying rates. The solution for the case of no temperature differential across the wall was not stable for any but the larger space depths combined with the smaller vent gap sizes. Unstable solutions are denoted by the lack of information in the table. Instability is a function of the iterative computational scheme used, not because the flow will necessarily be unstable. That does not imply that unstable airflow will not occur. In fact, it is likely under some conditions.

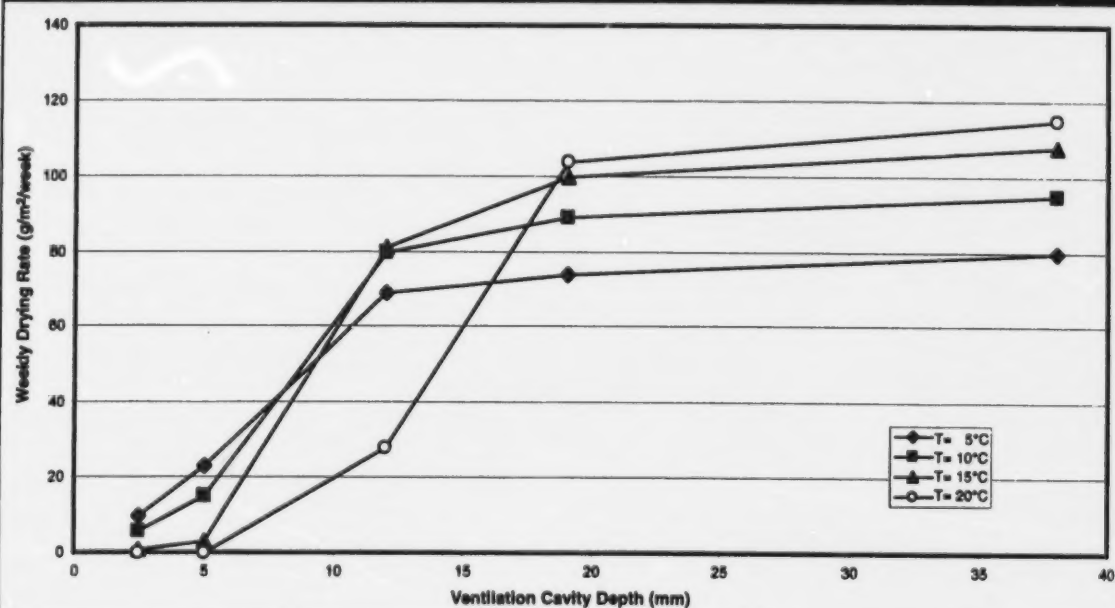
Again, for the specific case involving a 19-mm ventilation cavity and 12-mm ventilation gaps at the top and bottom (S19-12), the relative drying rate over the range $5/10/15/20^{\circ}\text{C}$, using the 5°C case as the reference, results in ratios of 1.0/1.19/1.38/--. The last ratio value is not provided because the ventilation solution for the 20°C case was not stable.

Drying of the wall, when both the inner and outer temperatures are identical, is a worst case scenario because the thermal driving forces are absent. Diffusion is still possible, but the dwell time of air in the ventilation cavity is long.

Table 6: Effect of ventilation parameters and chamber temperature on the weekly drying rate (g/m²/week) neutral pressure, decoupled stucco, chamber RH = 50%.

Vent Gap Height (mm)	Ventilation Cavity Width (mm)						Ventilation Cavity Width (mm)					
	38	19	12	5	2.5	1	38	19	12	5	2.5	1
Chamber Temperature = 5°C												
1	78	70	67	25	10	10	89	82	76	17	7	7
2.5	80	74	69	23	9	N/A	95	89	80	15	6	N/A
5	84	76	72	25	N/A	N/A	99	91	83	17	N/A	N/A
12	84	77	73	N/A	N/A	N/A	99	92	84	N/A	N/A	N/A
19	82	77	N/A	N/A	N/A	N/A	99	93	N/A	N/A	N/A	N/A
38	80	N/A	N/A	N/A	N/A	N/A	97	N/A	N/A	N/A	N/A	N/A
Chamber Temperature = 10°C												
1	97	88	76	4	2	2	94	81	27	-	-	-
2.5	108	100	81	3	1	N/A	115	104	28	-	-	N/A
5	113	104	85	4	N/A	N/A	126	108	36	-	N/A	N/A
12	115	108	86	N/A	N/A	N/A	134	-	-	N/A	N/A	N/A
19	116	108	N/A	N/A	N/A	N/A	-	-	N/A	N/A	N/A	N/A
38	115	N/A	N/A	N/A	N/A	N/A	-	N/A	N/A	N/A	N/A	N/A
Chamber Temperature = 15°C												
1	97	88	76	4	2	2	94	81	27	-	-	-
2.5	108	100	81	3	1	N/A	115	104	28	-	-	N/A
5	113	104	85	4	N/A	N/A	126	108	36	-	N/A	N/A
12	115	108	86	N/A	N/A	N/A	134	-	-	N/A	N/A	N/A
19	116	108	N/A	N/A	N/A	N/A	-	-	N/A	N/A	N/A	N/A
38	115	N/A	N/A	N/A	N/A	N/A	-	N/A	N/A	N/A	N/A	N/A
Chamber Temperature = 20°C												
1	97	88	76	4	2	2	94	81	27	-	-	-
2.5	108	100	81	3	1	N/A	115	104	28	-	-	N/A
5	113	104	85	4	N/A	N/A	126	108	36	-	N/A	N/A
12	115	108	86	N/A	N/A	N/A	134	-	-	N/A	N/A	N/A
19	116	108	N/A	N/A	N/A	N/A	-	-	N/A	N/A	N/A	N/A
38	115	N/A	N/A	N/A	N/A	N/A	-	N/A	N/A	N/A	N/A	N/A

Figure 4: Effect of temperature in the chamber on the weekly drying rates as a function of ventilation cavity depth of a vent gap size of 2.5 mm, decoupled stucco, RH = 50%.



The effect of variation in the temperature differentials across the wall is illustrated for the 2.5-mm vent gap height size in Figure 4. Again, vent spaces in the order of 12 mm and over were effective for drying. For vent spaces 5 mm and under, drying rates were significantly lower.

Both Table 6 and Figure 4 show that chamber temperatures above the set point are likely to increase the rate at which drying will take place.

Coupled Stucco Walls

When stucco is applied to the wall in a manner that does not isolate the stucco from absorption/desorption of moisture from either the wall behind or from the air in the chamber, moisture redistribution and drying behaviour become more complex. There are competing mechanisms for moisture from the wall to escape by ventilation (as before) and by diffusion through the stucco. There are, of course, additional mechanisms that are common to both the coupled and decoupled stucco cases for removal of moisture. Should the conditions be appropriate for condensation on surfaces that can no longer absorb additional moisture, and the water films retained can no longer retain their position against the force of gravity, then drainage is possible. These mechanisms were not shown to occur for the simulations done for this study.

The initial moisture conditions of the stucco were found to be important in assessing the magnitude of moisture lost from the wall by ventilation or by diffusion transfer through the stucco. When a test wall with a stucco cladding is first exposed to a particular environment, there is a period during which it will experience either a gain or a loss in moisture depending on its equilibrium condition before that exposure. This will be illustrated further in this section. To avoid this experimental effect, the initial moisture content of the stucco was set internally in the WALLDRY program so it would be in equilibrium with the chamber conditions. Thus, for each of the cases where the RH of the chamber is set to a different steady-state condition, a different moisture content is set so the subsequent changes in moisture levels under the intended experimental conditions are not dwarfed by gains or losses by the stucco itself.

Question #4: For coupled stucco cladding, what is the influence of chamber RH on the drying rates of walls? How much moisture leaves by diffusion compared with moisture that leaves by venting?

Only one set of chamber conditions was investigated for coupled siding. It involved varying the influence of the RH of the chamber.

Again, the RH conditions were allowed to range from 50 per cent to 80 per cent in increments of 10 per cent for each set of 21 parameter combinations. In each case, the initial moisture content of the stucco was adjusted for those conditions to avoid large initial conditioning changes. The eight-day simulations, ignoring the first day, were sufficiently linear and representative of the succeeding weeks that the initial drying rates were considered to be representative.

The results are presented in tables 7 and 8. Table 7 is parallel to Table 5 except that the data in Table 7 represents the net drying rate for the wood elements in these walls. This usually resulted in deposition of more moisture in the wood panel sheathing than was there initially. What is striking, and expected, is that significantly more moisture was able to dry from the walls by diffusion through the stucco so the total change was greater. Table 8 reflects the change in moisture in the stucco for the same one-week drying period. A positive value represents a loss in moisture from the moisture condition, seven days earlier. A negative mass value represents the amount of moisture retained by the stucco compared with the quantity held seven days earlier. These values indicate how some of the moisture loss, especially for relatively closed stucco systems, was able to leave the wall. While the amounts are small, they represent significant improvement in drying capability. The reference stucco wall example used earlier (S19-12) results in ratios of the relative drying over the range 80/70/60/50 per cent using the 80 per cent case as a reference, of 1.00/1.15/1.29/1.44 (compared with 1.0/1.20/1.39/1.57 for the decoupled stucco case). The relative drying rate of closed stucco systems (with a small amount of ventilation possible) is radically improved.

Figure 5 was prepared to show the drying rates for the specific vent gap size of 2.5 mm. This is to parallel the information prepared in Figure 3 for decoupled stucco walls. This shows the general improvement in wall drying and, in particular, for drying when the ventilation cavity depth is less than 12 mm.

Table 7: Effect of ventilation parameters and chamber RH on the weekly drying rate from wood framing (g/m²/week) neutral pressure, coupled stucco, chamber temperature 5 °C

Vent Gap Height (mm)	Ventilation Cavity Depth (mm)						Ventilation Cavity Depth (mm)					
	38	19	12	5	2.5	1	38	19	12	5	2.5	1
Chamber RH = 50%												
1	99	83	82	61	59	58	91	75	74	56	54	53
2.5	98	87	79	56	54	N/A	90	79	71	50	49	N/A
5	101	88	86	61	N/A	N/A	93	80	78	56	N/A	N/A
12	98	89	86	N/A	N/A	N/A	90	80	78	N/A	N/A	N/A
19	97	89	N/A	N/A	N/A	N/A	88	80	N/A	N/A	N/A	N/A
38	92	N/A	N/A	N/A	N/A	N/A	84	N/A	N/A	N/A	N/A	N/A
Chamber RH = 60%												
1	82	66	66	50	48	47	74	57	56	43	41	40
2.5	82	70	65	44	42	N/A	73	61	53	37	35	N/A
5	84	71	69	50	N/A	N/A	75	62	60	43	N/A	N/A
12	81	71	69	N/A	N/A	N/A	72	62	60	N/A	N/A	N/A
19	79	71	N/A	N/A	N/A	N/A	70	62	N/A	N/A	N/A	N/A
38	75	N/A	N/A	N/A	N/A	N/A	65	N/A	N/A	N/A	N/A	N/A
Chamber RH = 70%												
1	82	66	66	50	48	47	74	57	56	43	41	40
2.5	82	70	65	44	42	N/A	73	61	53	37	35	N/A
5	84	71	69	50	N/A	N/A	75	62	60	43	N/A	N/A
12	81	71	69	N/A	N/A	N/A	72	62	60	N/A	N/A	N/A
19	79	71	N/A	N/A	N/A	N/A	70	62	N/A	N/A	N/A	N/A
38	75	N/A	N/A	N/A	N/A	N/A	65	N/A	N/A	N/A	N/A	N/A
Chamber RH = 80%												
1	82	66	66	50	48	47	74	57	56	43	41	40
2.5	82	70	65	44	42	N/A	73	61	53	37	35	N/A
5	84	71	69	50	N/A	N/A	75	62	60	43	N/A	N/A
12	81	71	69	N/A	N/A	N/A	72	62	60	N/A	N/A	N/A
19	79	71	N/A	N/A	N/A	N/A	70	62	N/A	N/A	N/A	N/A
38	75	N/A	N/A	N/A	N/A	N/A	65	N/A	N/A	N/A	N/A	N/A

Table 8: Net drying from stucco as a function of vent characteristics and chamber RH (g/m²/week) neutral pressure, coupled stucco, chamber temperature 5 °C

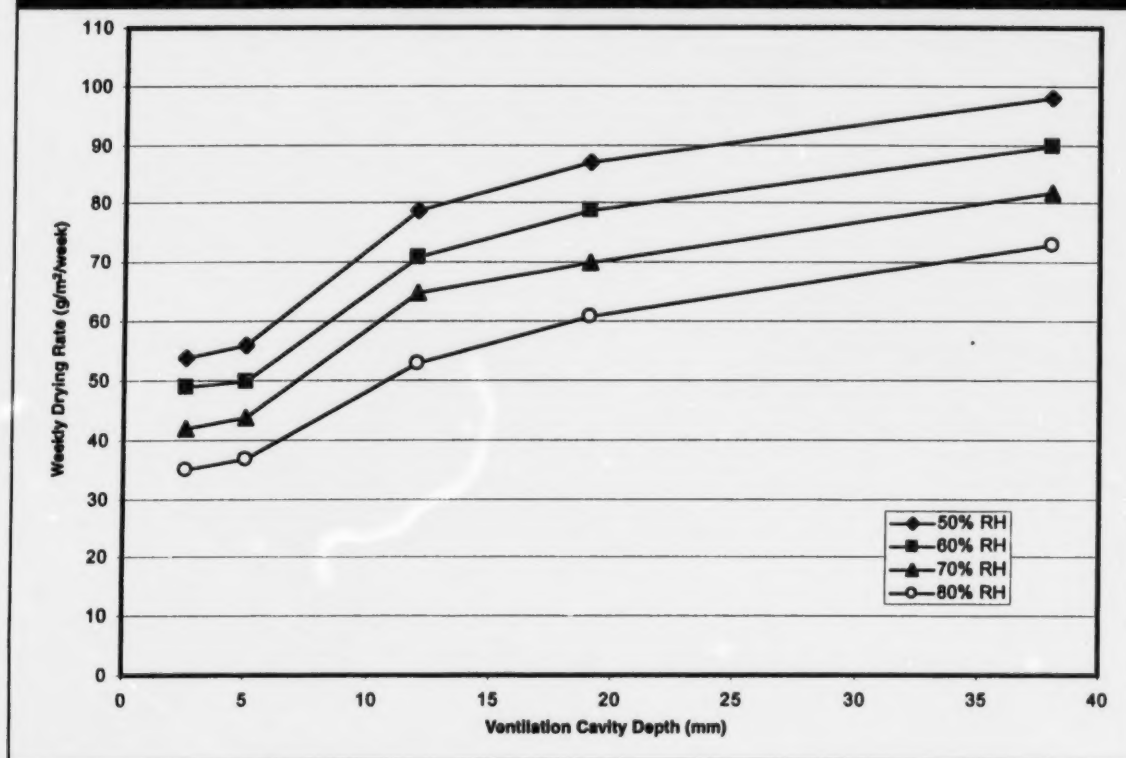
Vent Gap Height (mm)	Ventilation Cavity Depth (mm)						Ventilation Cavity Depth (mm)					
	38	19	12	5	2.5	1	38	19	12	5	2.5	1
Chamber RH = 50%												
1	0	2	0	-25	-42	-43	3	6	4	-21	-35	-36
2.5	4	5	4	-24	-36	N/A	6	8	7	-18	-29	N/A
5	3	5	4	-26	N/A	N/A	5	8	7	-21	N/A	N/A
12	3	5	4	N/A	N/A	N/A	4	8	7	N/A	N/A	N/A
19	2	5	N/A	N/A	N/A	N/A	4	8	N/A	N/A	N/A	N/A
38	2	N/A	N/A	N/A	N/A	N/A	4	N/A	N/A	N/A	N/A	N/A
Chamber RH = 60%												
1	8	10	8	-15	-26	-27	12	17	15	-6	-16	-16
2.5	9	12	12	-11	-20	N/A	15	19	20	-2	-6	N/A
5	8	12	12	-15	N/A	N/A	12	19	18	-6	N/A	N/A
12	6	12	12	N/A	N/A	N/A	9	18	19	N/A	N/A	N/A
19	5	12	N/A	N/A	N/A	N/A	8	18	N/A	N/A	N/A	N/A
38	5	N/A	N/A	N/A	N/A	N/A	6	N/A	N/A	N/A	N/A	N/A
Chamber RH = 70%												
1	8	10	8	-15	-26	-27	12	17	15	-6	-16	-16
2.5	9	12	12	-11	-20	N/A	15	19	20	-2	-6	N/A
5	8	12	12	-15	N/A	N/A	12	19	18	-6	N/A	N/A
12	6	12	12	N/A	N/A	N/A	9	18	19	N/A	N/A	N/A
19	5	12	N/A	N/A	N/A	N/A	8	18	N/A	N/A	N/A	N/A
38	5	N/A	N/A	N/A	N/A	N/A	6	N/A	N/A	N/A	N/A	N/A
Chamber RH = 80%												
1	8	10	8	-15	-26	-27	12	17	15	-6	-16	-16
2.5	9	12	12	-11	-20	N/A	15	19	20	-2	-6	N/A
5	8	12	12	-15	N/A	N/A	12	19	18	-6	N/A	N/A
12	6	12	12	N/A	N/A	N/A	9	18	19	N/A	N/A	N/A
19	5	12	N/A	N/A	N/A	N/A	8	18	N/A	N/A	N/A	N/A
38	5	N/A	N/A	N/A	N/A	N/A	6	N/A	N/A	N/A	N/A	N/A

Question #5: What difficulties will be experienced in relating moisture loss and redistribution of moisture in walls compared with total mass lost/gained during an experiment on drying?

To test this question, five-month simulations were conducted on two walls with coupled stucco (19-mm space and 38-mm space—both with the same vent gap height of 12 mm). Two chamber conditions were chosen (50 and 70 per cent RH) while maintaining the same chamber temperature

of 5°C. In each case, the equilibrium moisture content of the stucco was set to that condition for the chamber RH, as well as above or below that condition in separate simulations. When there was to be a mismatch in conditions, for example, with the chamber set to 50 per cent RH, the stucco was assumed to have attained equilibrium conditions at 70 per cent RH and vice versa. This is to test the situation in practice. It is unlikely that the stucco will ever be at the initial chamber conditions, unless the chamber starts out at the

Figure 5: The effect of RH conditions in the chamber showing the effect of ventilation cavity depth on weekly drying rates when stucco is coupled, vent gap size 2.5 mm, $T = 5^\circ\text{C}$



same conditions as the "indoor" case before insertion of a wall into the test position.

The total mass change for each case is shown in figures 6 and 7, for the two walls respectively. The drying behaviour of the two walls is similar, but the wall with the 38-mm ventilation cavity dries at a faster rate, permitting about seven per cent more moisture to escape. Referring to Figure 6, it is apparent that if the stucco has been preconditioned at a different moisture content, it may take from 15 to 30 days before the drying rate reflects the net moisture loss from the wood elements in the wall. Consequently, to be able to track the moisture gain and loss in particular layers, it is necessary that there be sufficient instrumentation to measure the actual initial conditions of both the wood and stucco in the wall, as well as subsequent changes that take place during the experiment.

Of particular interest is the case of the 70 per cent RH chamber test, with the stucco at an equilibrium for 50 per cent RH. It is expected that, for a while, the wall may not appear to lose weight. The stucco will be gaining moisture while at the same time losing moisture through ventilation in the cavity behind the stucco. Each wall will behave somewhat differently, depending on the balance between loss of moisture from the wall by either ventilation or diffusion, or both, and the direct gain or loss of moisture by the stucco.

Question #6: What are the moisture loss distributions in the walls, and the moisture gradients in different elements of the walls? As already noted, even with simple walls, a large amount of information could be generated for each wall. The WALLDRY program output module was tailored to provide only some information of interest. This information can be

Figure 6: Total weight change expected to take place under different conditions for wall S19-12

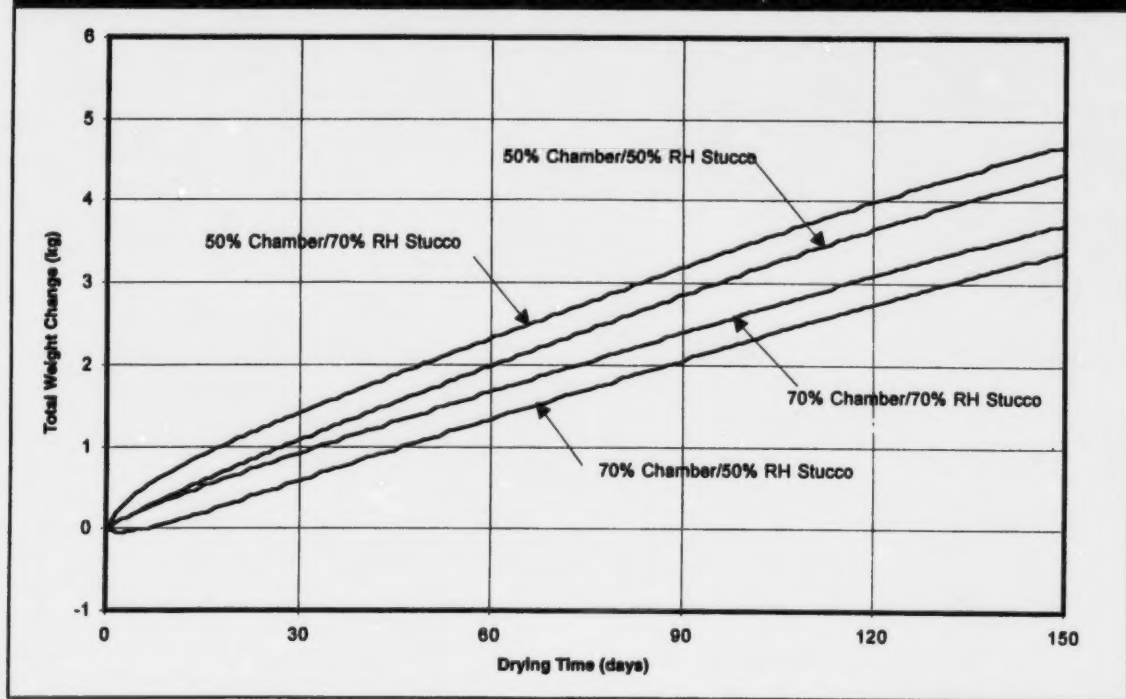
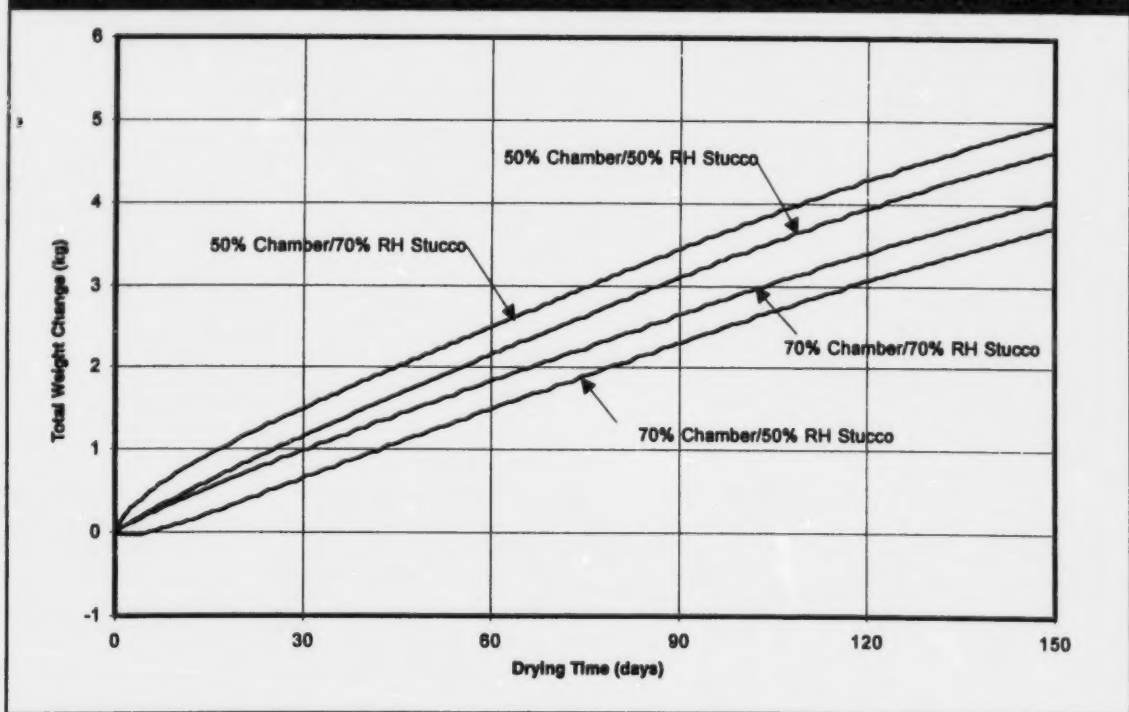


Figure 7: Total weight change expected to take place under different conditions for wall S38-12



imported into a spreadsheet program with some pre-formatted charts available for examination. The typical wall chosen to illustrate the changes taking place is S19-12, one of the test walls discussed under Question #6.

The specific example case chosen involves 70 per cent RH conditions, and stucco that has acclimatized to a lower initial RH, say at 50 per cent conditions. The EDRA project indoor RH condition is likely to be even lower, say 40 per cent, but this example illustrates the order of magnitude of changes that may be expected.

The summary results are shown in figures 8, 9, 10 and 11. Figure 8 shows the total moisture lost or gained by the studs, the OSB sheathing, the stucco cladding and the total wall. All positive values are moisture lost to the element/wall; a negative weight change represents moisture gained by the element.

Figure 9 shows the typical rapid moisture lost by the faces of the wetted studs and the redistribution of that moisture to other elements in the wall. The moisture content of the core was assumed to be 25 per cent initially. The core of the lumber framing continues to gain moisture for some time until the shell of the lumber dries enough for the core to start drying out as well. The WALLDRY program treats the stud elements as uniform single layers without accounting for the thermal or moisture gradient between the inner and outer faces of the wall cavity. There is likely to be some difference across the depth of the wall studs, but the initial formulation of the code in the 1980s, due to the limitations in size of the program under DOS, did not permit selection of a finer grid.

Figure 10 shows the moisture distribution on the inner face of the OSB sheathing from the bottom to the top of the wall (elements 1, 5 and 9). The bottom element takes longer to gain moisture and to dry because the flow of cooler air at the base of

Figure 8: Drying from each of the major elements of wall S19-12, with the 12-mm vents open at the top and bottom, chamber conditions 7% RH and 5 C with the stucco preconditioned at 50% RH

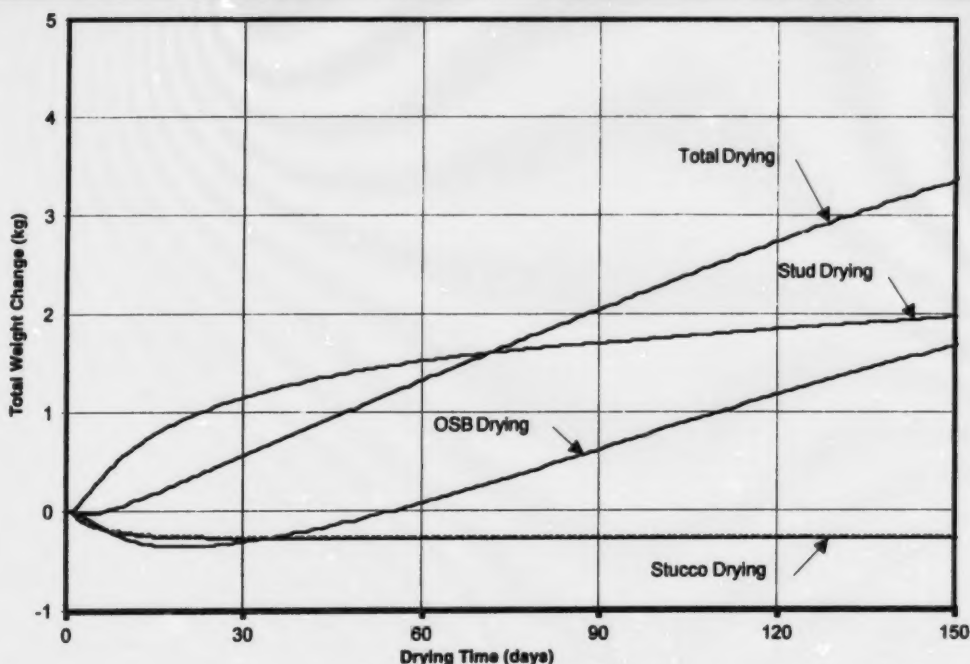


Figure 9: Drying from the shell and core of wood framing, top and bottom vents open for wall S19-12, chamber conditions at 70% RH and 5 C, stucco initially preconditioned at 50% RH

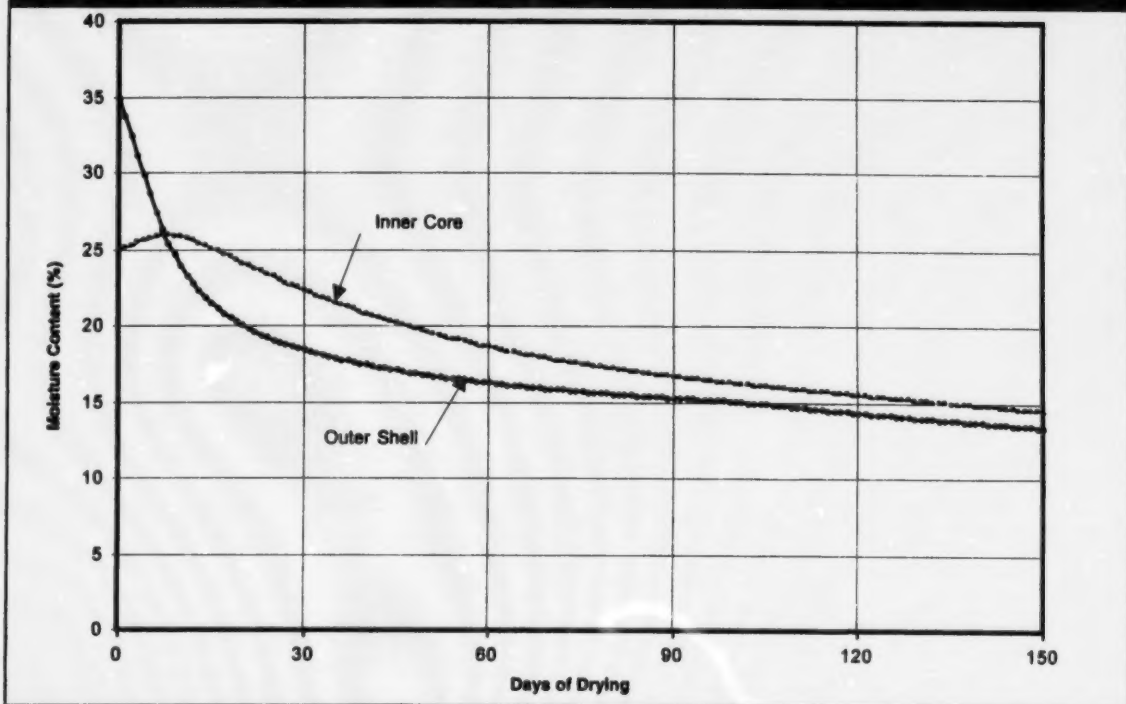


Figure 10: Drying of the inner face layer of OSB sheathing for wall S19-12 with 12-mm vents open top and bottom, chamber conditions at 70% RH and 5 C with the stucco preconditioned at 50% RH

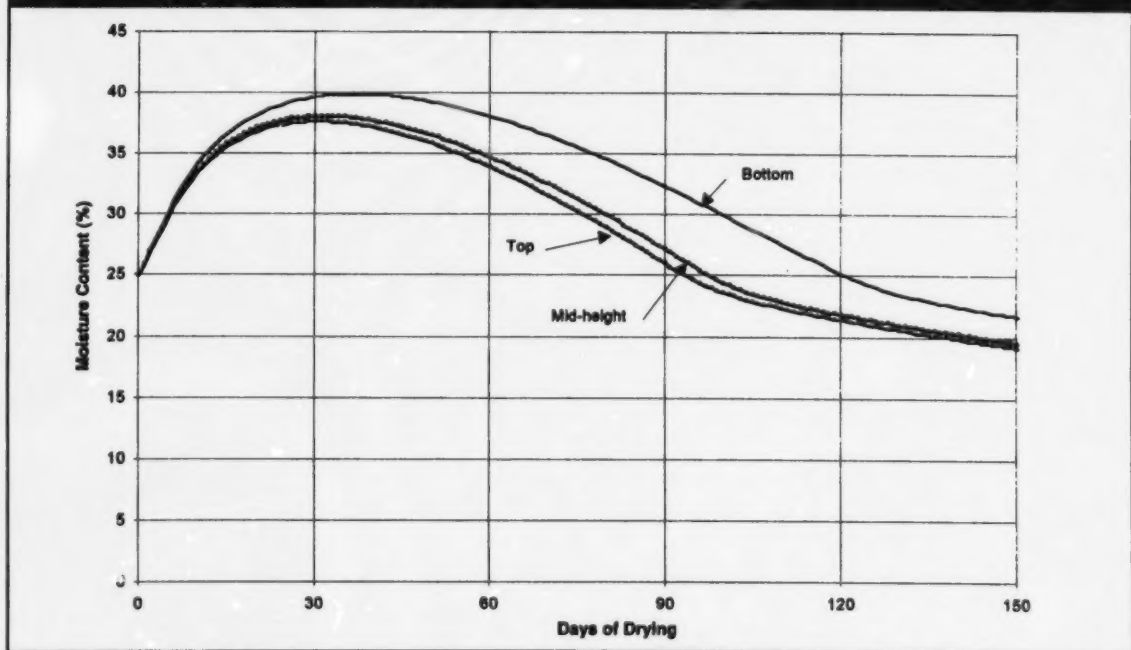
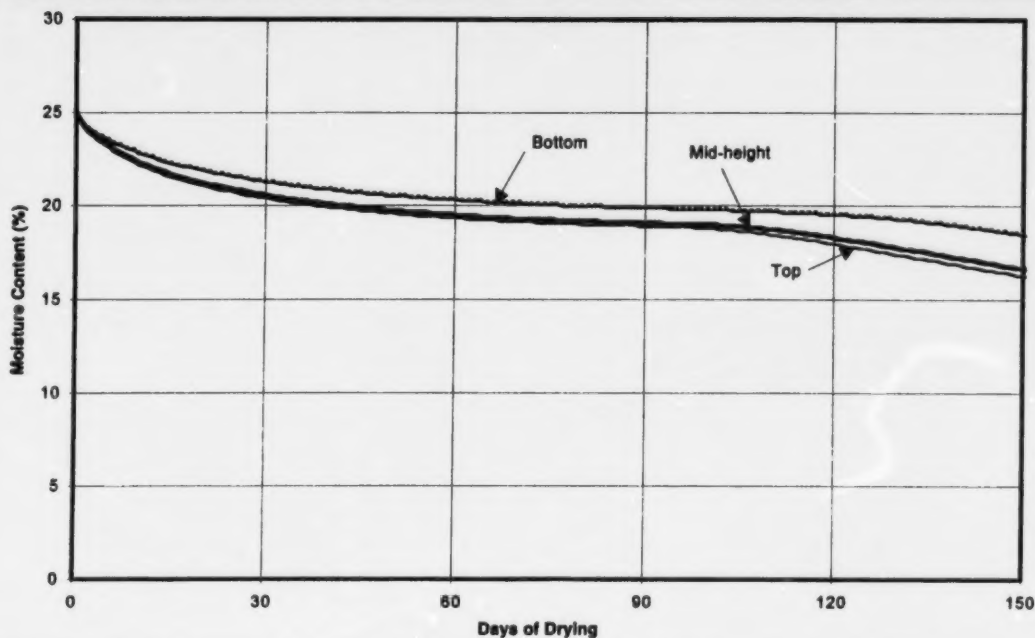


Figure 11: Drying of outer layer of OSB sheathing for wall S19-12 with top and bottom vents open at 12 mm, chamber conditions at 70% RH and 5 C with stucco preconditioned at 50% RH



the wall into the ventilation space reduces its ability to dry the wall. As the air warms and rises up the ventilation space, it is better able to take on additional moisture. This allows more drying to take place at the top of the wall than at its base. The inner face of the OSB sheathing is also the layer on which condensation of water vapour from the studs is deposited. In this case, there is insufficient drying in five months to bring that moisture level to 15 per cent (bulk moisture content basis) below which it is necessary to prevent mold growth.

Figure 11 shows that the outer layer of the OSB sheathing does not experience the same degree of moisture gain, as it is losing its moisture to the ventilation space through two layers of 30-minute building paper. Even in this case, under these conditions, the moisture content did not fall below 15 per cent in this five-month simulation. Steady state conditions are not a likely real-life situation, so the duration of drying determined from this test is not relevant, except perhaps in relative terms.

Question #7: What are the moisture loss distributions in walls when the ventilation gap at the top is closed?

To illustrate this case, the same wall example was used as for the previous question. The coefficients for the top vent were made as resistive as for the virtual vent gaps in the body of the stucco wall.

Figures 12, 13, 14 and 15 parallel figures 8, 9, 10 and 11 for the fully open-vented cavity. The total drying rates shown in Figure 12 are somewhat altered. The studs dry out within the cavity as before. But the total moisture change is significantly less, largely because there is no airflow through the ventilation cavity. But, the temperature of that air and its relative humidity are higher than before and more moisture is able to leave by diffusion through the stucco. Also, a larger quantity of moisture is retained in the stucco. For example, for the vent-open case, the inner and outer moisture contents of the stucco faces were both 0.89 per cent. For the closed-top vent case, the inner and outer moisture contents were 0.93 per cent and 1.31 per cent respectively. The total weight loss was 39 per cent less with the top vent closed.

Figure 13 shows that the stud moisture content varied very much as for the vent-open case.

Figure 14 shows that, at all levels in the wall, the moisture content at the inner layer of OSB sheathing was the same, largely because there was no airflow to remove moisture in a differential manner. It took most of the five-month drying period for the OSB in the wall to recover to its original high moisture level.

Figure 15 shows that because the drying rate was slow, the moisture content of the outer layer of OSB sheathing remained at a relatively higher level throughout the drying period.

As a test of the effect when a fully closed top vent will not be achieved, and some built-in leakage can occur, we assume that a vent size of 1 mm will be available to permit some ventilation. This case was run and the results are shown in figures 16, 17 and 18.

In Figure 18, which is parallel to Figure 8 (which has no restriction on flow being a 12-mm vent) and Figure 12 (which was fully closed), we see that the result is very nearly similar to Figure 8. The total weight loss from the wall with a partially open top vent was only three per cent less than for the fully open top vent (12 mm in this example). The total weight loss for a fully closed top vent was 39 per cent less than the fully open top vent. In other words, a small amount of flow out of the top of the ventilation cavity is very beneficial in assisting removal of moisture from the wall. Given that it is so important, it should not be left to chance. Some reliable means should be provided to permit some airflow for venting moisture from behind stucco walls. Provision of a small opening need not encourage entry of wind-driven rain into that space.

Figure 12: Drying from each of the major elements in wall S19-12, with the top vent closed, chamber conditions at 70% RH and 5 C with stucco preconditioned at 50% RH

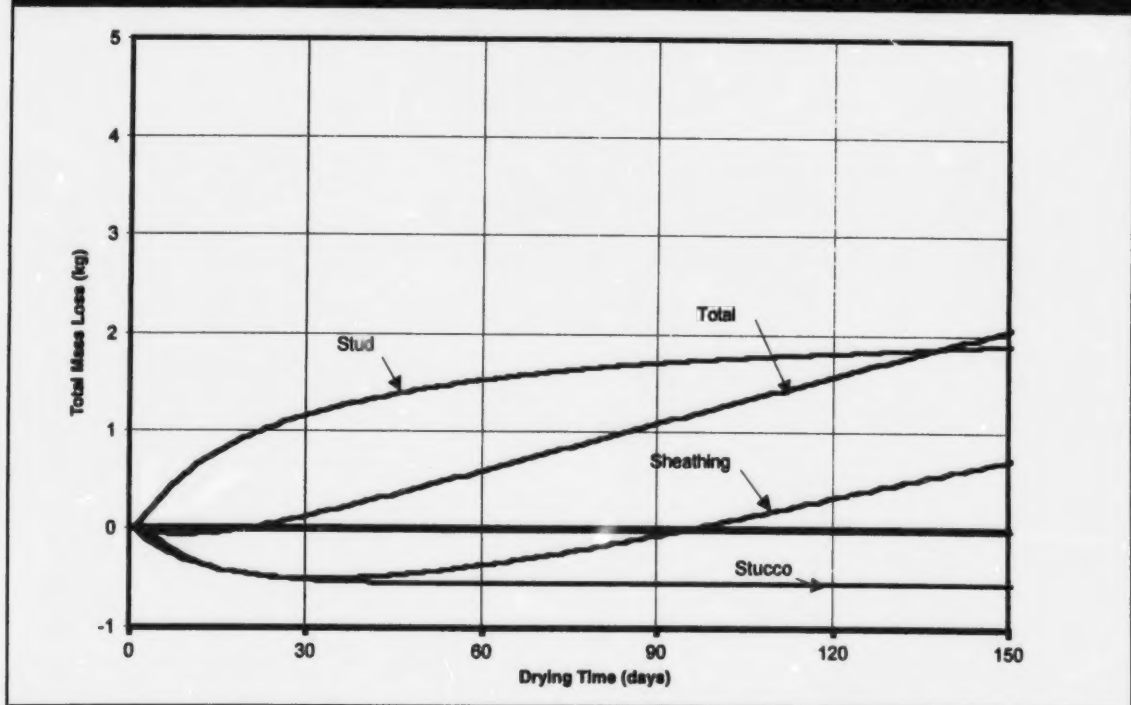


Figure 13: Drying of the outer shell and inner core of the lumber framing, wall S19-12, chamber conditions at 70% RH and 5 C, stucco initially preconditioned at 50% RH.

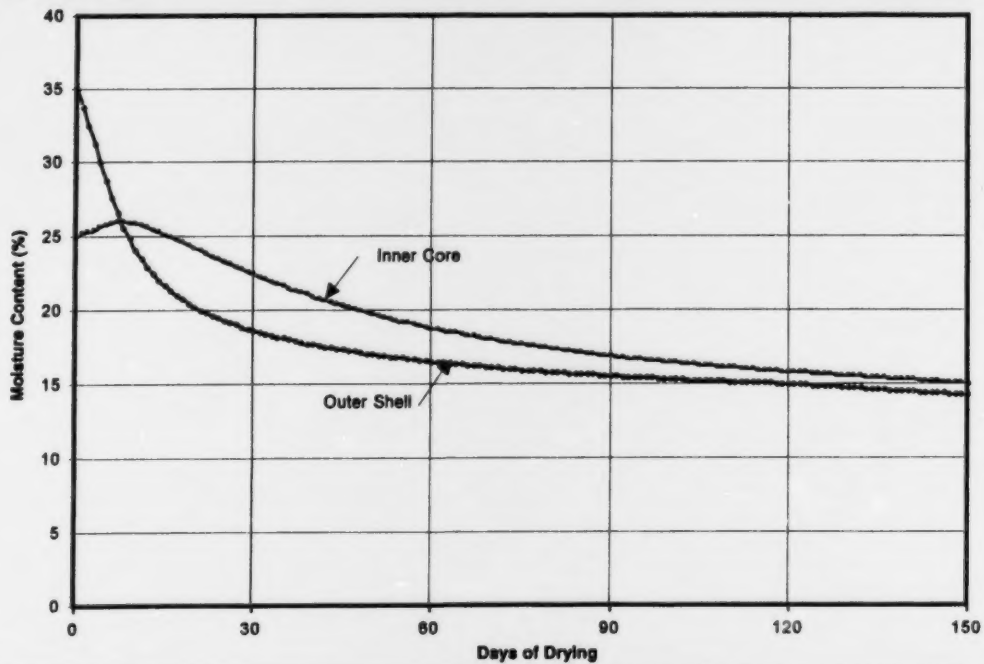


Figure 14: Drying curve for the inner face layer of OSB sheathing for wall S19-12 with the top vents closed, chamber conditions at 70% RH and 5 C with the stucco preconditioned at 50% RH.



Figure 15: Drying of outer layer of OSB sheathing in wall S19-12 with the open top closed, chamber conditions at 70% RH and 5 C with the stucco preconditioned at 50% RH

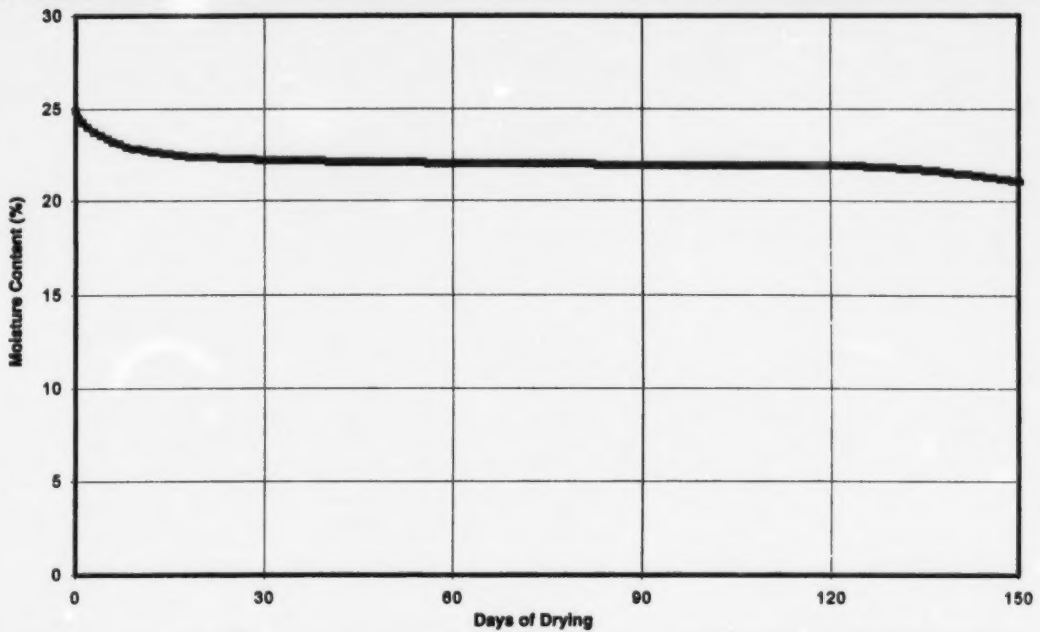


Figure 16: Drying from each of the major elements in wall S19-12, with the top vent partially closed gap (1 mm), chamber conditions at 70% RH and 5 C with the stucco preconditioned at 50% RH

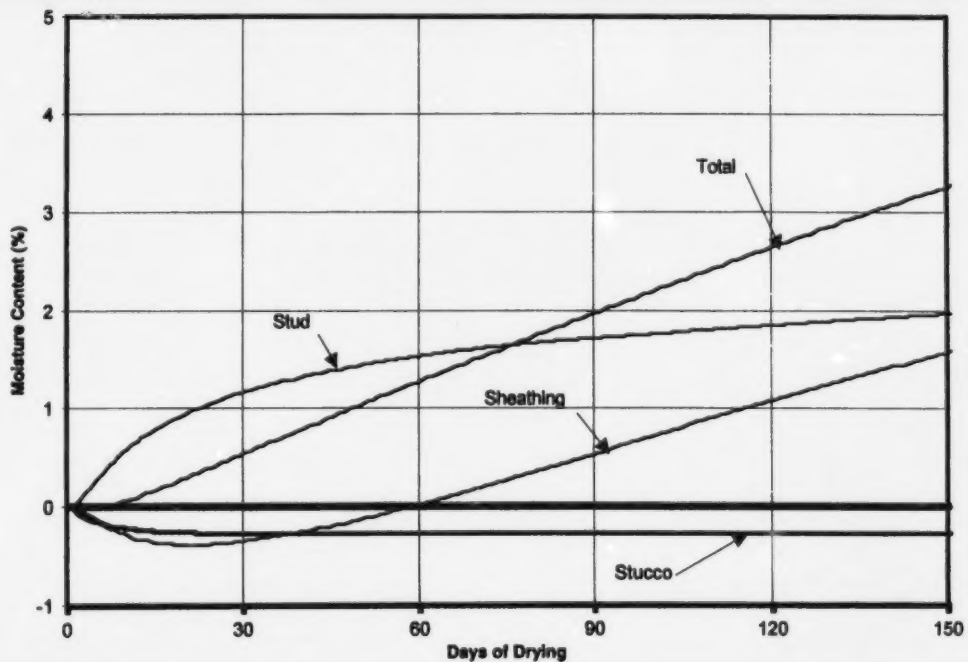


Figure 17: Drying curve for the inner face of the OSB sheathing, wall S19-12, with the top vent partially closed gap (1 mm), chamber conditions at 70% RH and 5 C with the stucco preconditioned at 50% RH

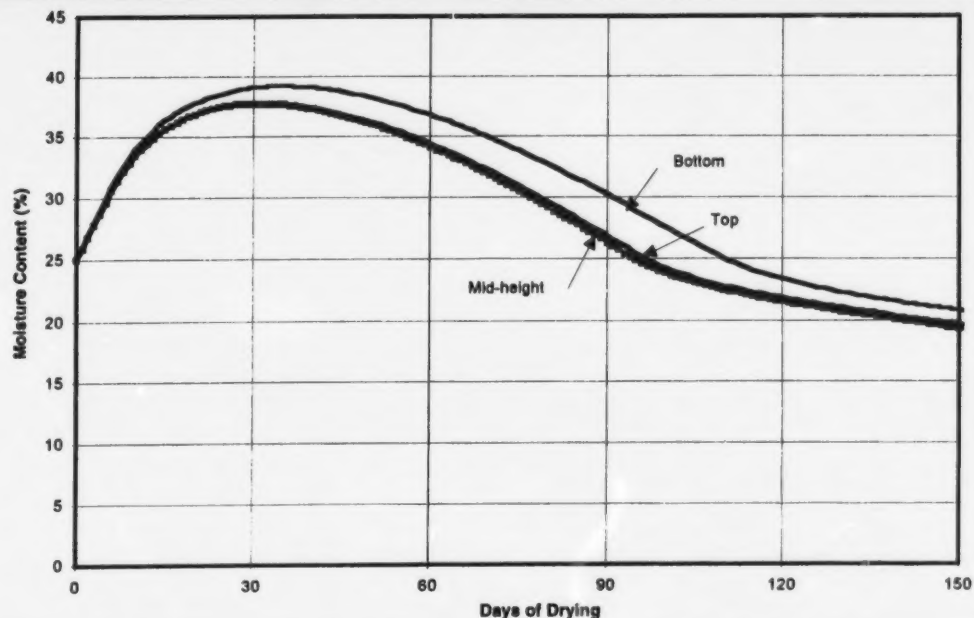
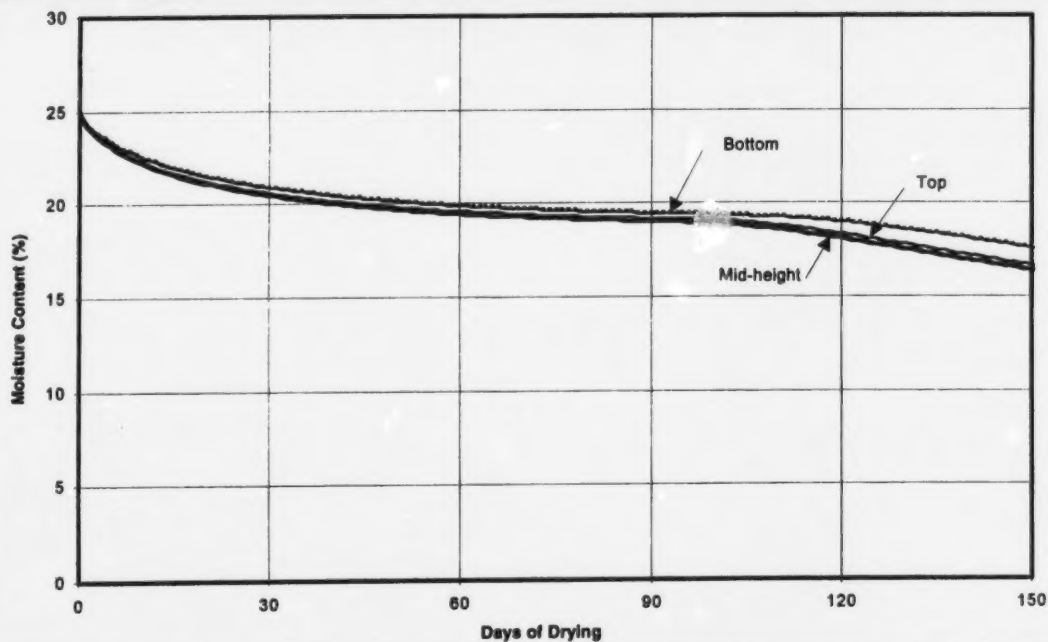


Figure 18: Drying of outer layer of OSB sheathing in wall S19-12, with the top vent partially closed gap (1 mm), chamber conditions at 70% RH and 5 C with the stucco preconditioned at 50% RH



Question #8: What effect does a simulated wind have on drying rates for a typical base case wall [S19-05]?

The results for this case are shown in Table 9. Contrary to expectations, the total drying rate of the wall was slowed. The coupled stucco was assumed to have the same initial equilibrium RH condition as the environmental chamber. Over the five-month period, the drying was 4.268 kg without a wind, and 4.181 kg with a wind. The main explanation is that the wind induced a velocity in the ventilation cavity that was almost double that without an applied wind. The temperature was cooler when the wind was applied, and the RH was slightly higher. The end result was that slightly less moisture could be removed by ventilation. Also, the stucco drew off slightly more of the moisture in the ventilation cavity because it was warmer when there was no wind. The difference in total moisture loss was two per cent less over that entire period when the wind was applied. A higher RH chamber would have inhibited drying somewhat more. A more open ventilation cavity would have encouraged greater flow, with the same effect.

This examination does not account for a characteristic of ventilation cavities for which there is no information and which may yet reverse the above finding. The airflow properties of the ventilation cavity system were assumed to be laminar, and the specification of the flow coefficients reflects that. At very low velocities, it may well provide considerable resistance to flow. However, as the velocity of the air increases, depending on the surface characteristics, turbulence may be generated, decreasing the resistance to flow and significantly improving mixing of air and removal of the moisture. Determining the flow coefficients for air in ventilation cavities under low pressure differentials would be important to better understand the contribution of wind action to moisture removal, even under marginal conditions.

Existing stucco walls may also provide other avenues for air leakage. Within the field of the wall, small cracks may form, and these will

provide a means of air entry or exit to supplement intentional air leakage paths, just as in vinyl and wood-based siding systems. If this is a common occurrence, the effect can be modelled by assuming some airflow characteristics for what are now virtual joints in the stucco.

Question #9: What is the difference in drying rates when plywood is used instead of OSB, using the properties implemented in WALLDRY?

Only one case was run, that being for test wall S19-12PL, which is the same base wall as before but with 12.5 mm plywood instead of OSB, and for the normal chamber conditions currently proposed (5°C and 70 per cent RH). The stucco is considered coupled to the wall, and it is assumed to have an initial equilibrium condition compatible with the interior of the chamber.

Despite the apparent simplicity of the comparison, there is a complication that affects the results and the interpretation. Under the assumed input, the initial moisture content of the sheathing is assumed to be 25 per cent. This is moisture content on a dry weight basis. The current assumed mass of dry OSB is 24.93 kg, while for the plywood it is 20.24 kg. The mass of moisture held at a 25 per cent dry weight basis in the OSB is 6.233 kg and in the plywood it is 5.06 kg (i.e., 1.17 kg less water).

At the end of five months of drying under neutral pressure and no wind, the plywood was drier than the OSB, and the lumber in the wall with plywood was also drier. For example, the framing lumber in the plywood wall had shell/core moisture contents at the mid-height position in the wall of 12.13/13.41 per cent, while for the OSB sheathed wall the framing moisture contents were 13.41/14.48 per cent moisture. With more moisture to be removed, more time is required to reach the same moisture level. However, based on the diffusion properties noted in Chapter 8, it is probable that, for the same total initial moisture conditions, the plywood wall would dry more rapidly. The apparent total drying rate for the plywood sheathed wall was 0.0596 kg/week while for the OSB wall it was 0.0557 kg/week.

Questions #10: What is the effect of using 2 x 6 framing instead of 2 x 4 material?

As noted in posing this question, 57 per cent more moisture will be held in the framing because of the larger volume of material. A comparison with the drying of walls with 2 x 4 (38 x 89 mm) and 2 x 6 (38 x 189 mm) framing is not a question of showing that one size is better than the other, but rather showing how a wall with 2 x 6 framing behaves. The quantity of moisture held by a 2 x 6 wall, if the origin of the moisture is from outside the structure, should not be higher than for a 2 x 4 framed wall for a direct comparison. This does not mean that a simple reduction in the soaking time is sufficient to simulate this case for a wall with 2 x 6 framing. The actual initial distribution of moisture in walls subject to intrusion by leakage is probably affected by gravity, and the lower portion of walls will be more highly stressed than upper portions.

To illustrate the drying of a 2 x 6 framed wall wetted in the same way as the walls with 2 x 4 framing, the example test wall S19-12 is used again. Only two figures are provided. Figure 19 shows the total weight variation is parallel to others of this type earlier in the report. The total moisture loss is greater as there is more to be removed and as the wall is wetter for a longer time. Also, the wall sheathing is more permissive at high RH conditions. The OSB gained total moisture for about 40 days and did not regain its original high average moisture conditions until about 110 days into the simulation.

Figure 20 shows the moisture accumulation on the inner face of the OSB sheathing. This is the first case in which the rate at which condensation built up on the inner surface OSB sheathing layer more rapidly than it could be removed, and the pre-specified saturation level of 45 per cent was reached. Some drainage was possible, but it was retained in the wall.

This example draws attention to a matter noted in Chapter 4 concerning the absence of liquid mass transfer capability by the model. If it had been

possible to invoke that capability, a higher rate of moisture transmission would have occurred, and the moisture buildup would have been smaller. This example also encountered an artifact in the airflow sub-routine, which can only be described as a "drift" in the airflow convergence criterion. This allowed convergence to a solution to occur at lower exit air velocities than at inlet air velocities. As this case was not discovered early in the program modification, the problem was not resolved for this report. A scan of simulations done earlier showed that only a few cases had been similarly affected. Even in these cases, the moisture loss summaries, similar to that shown in Figure 19, all conformed to expected performance, and it is not expected that any of the conclusions drawn to this point are suspect.

Question #11: What are the drying rates when the polyethylene vapour barrier is not installed?

The example used to illustrate the changes that take place when the polyethylene vapour barrier is not installed is the S19-12 wall with the top vent fully closed.

The drying rates were found to be significantly higher. These changes are shown in figures 21, 22, 23 and 24 for the overall total drying rates, and the moisture contents in lumber framing, and the inner and outer faces of the OSB sheathing. The properties of the gypsum used for this simulation did not involve any vapour retardant paint on the inside face. The drying was fastest for this case compared with all cases run to this point. That is not to say whether this case would perform satisfactorily for chronic wetting conditions. Certainly, this construction approach, referred to as the airtight drywall approach (ADA), offers builders an opportunity to permit a significant proportion of a moisture load imposed during construction to dry. In cold climate regions, the final painting of the drywall with a vapour retardant paint must be delayed sufficiently to allow construction moisture to escape.

Figure 19: Drying of the main elements of the wall S19-12 with lumber framing, chamber RH of 50% and stucco cladding initially preconditioned to the same RH conditions

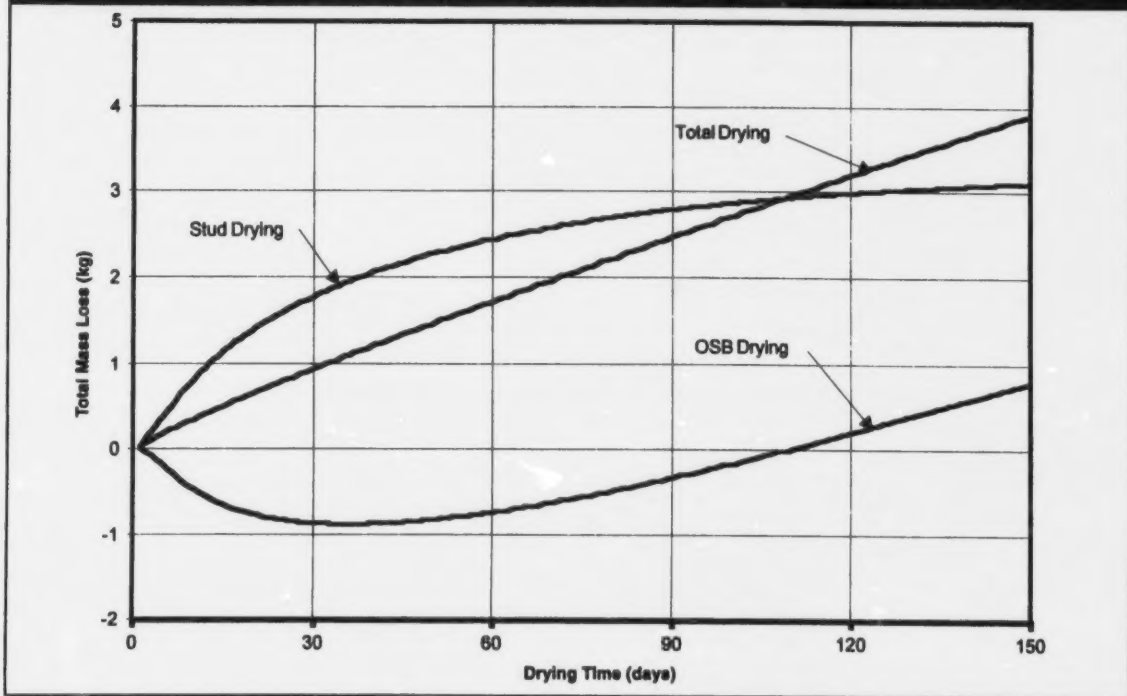


Figure 20: Moisture buildup in the inner layer of the OSB sheathing, wall S19-12 with 2 x 6 lumber framing, maximum moisture that could be held specified to be 45%.

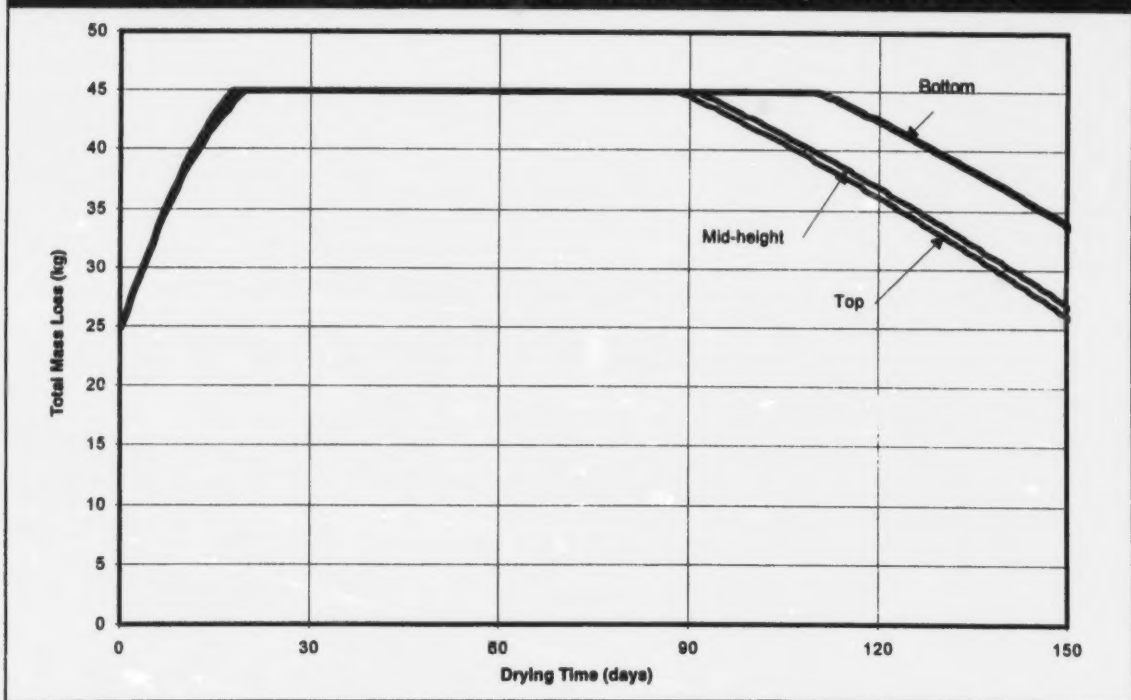


Figure 21: Drying from each major element in wall S19-12, polyethylene vapour barrier removed and top vent closed, chamber conditions at 70% RH and 5 °C with stucco initially preconditioned at 50% RH

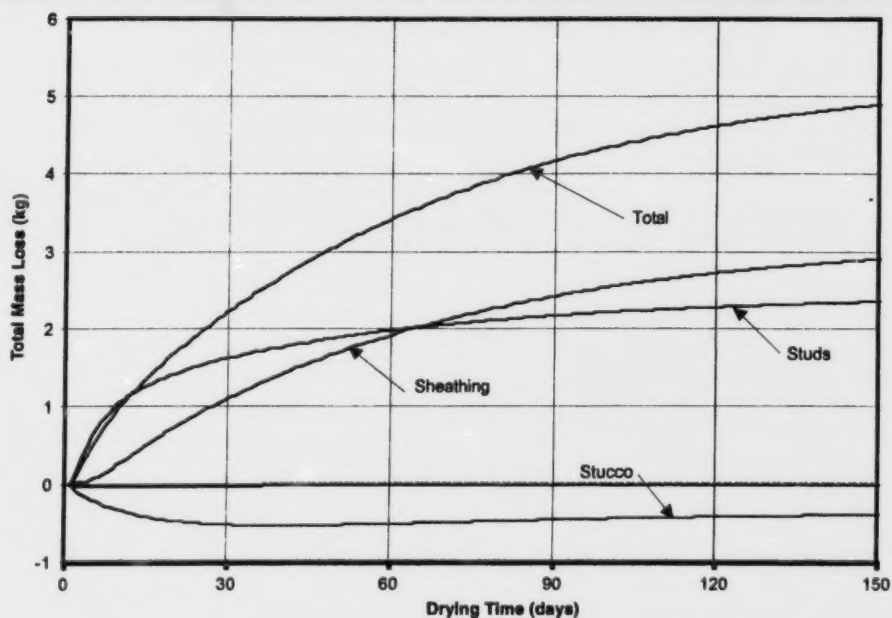


Figure 22: Drying of the outer shell and inner core of lumber framing, wall S19-12, polyethylene vapour barrier removed, top vent closed, chamber conditions at 70% RH and 5 °C with stucco initially preconditioned at 50% RH

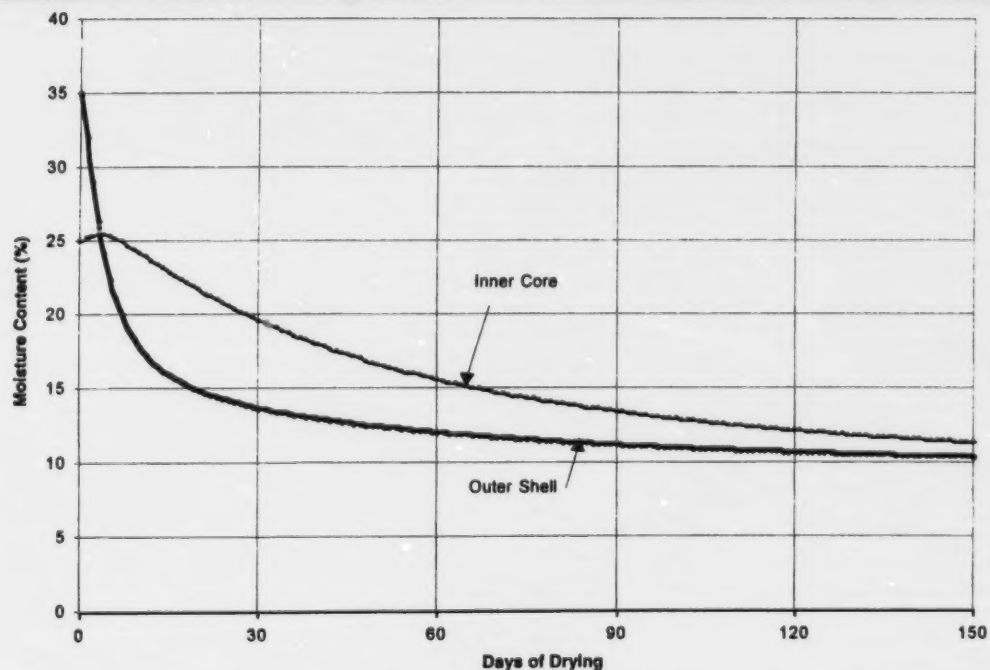


Figure 23: Drying curve for the inner face of the OSB sheathing, wall S19-12, polyethylene vapour barrier removed and top vent closed, chamber conditions at 70% RH and 5 C with stucco initially preconditioned at 50% RH

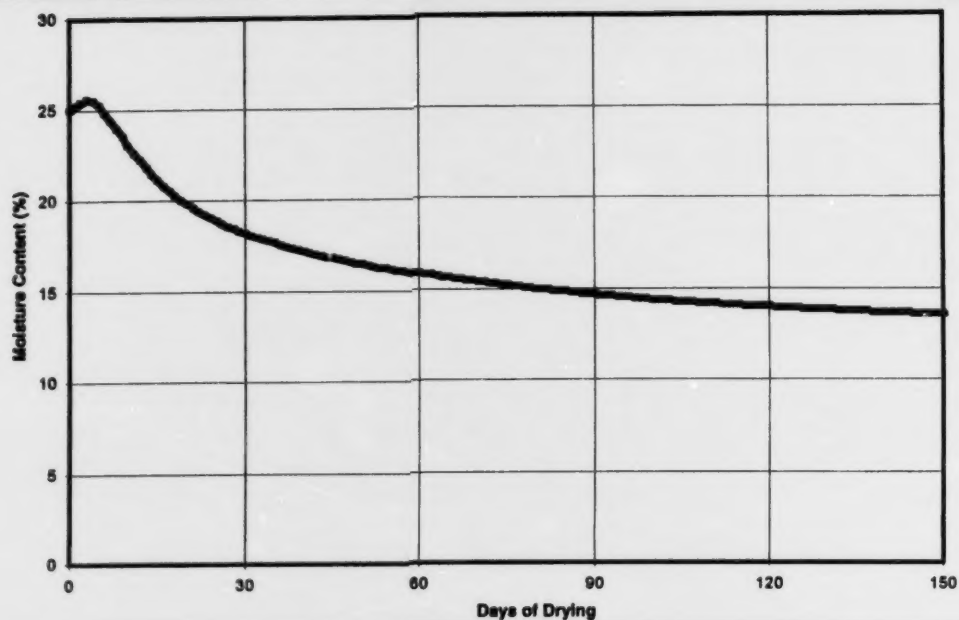
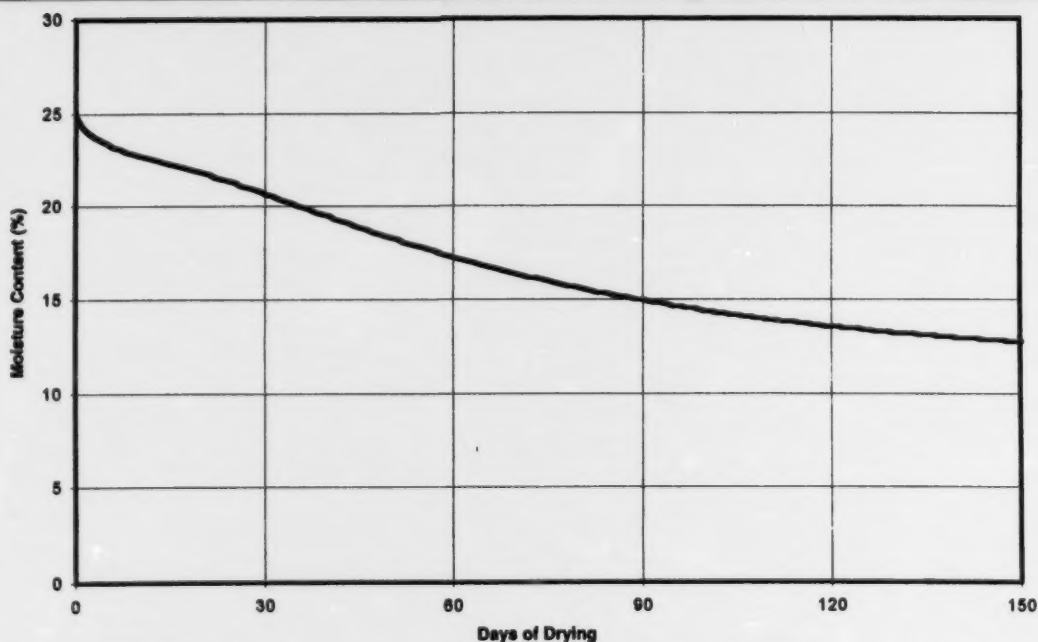


Figure 24: Drying of outer layer of OSB sheathing in wall S19-12, polyethylene removed and top vent closed, chamber conditions at 70% RH and 5 C with stucco initially preconditioned at 50% RH



Performance of Reference Walls

Two reference walls have been included in the EDRA project, and these simulations were done to compare their performance with the other stucco clad walls simulated in this report. It is worth pointing out now that poor drying, or poorer drying, of these reference walls does not imply that the performance of stucco walls behaving in a similar way is acceptable. The acceptable historic performance of more conventional walls may not be attributable to the specific materials used, but to the manner in which these walls and buildings were constructed.

Question #12: What is the drying performance of two reference walls, built using vinyl siding and wood siding subject to the same moisture load as used in this parametric study?

The examples used for this examination were files set up in the 1980s with air leakage characteristics based on bench top tests by RWDI (RWDI and Scanada, 1988; Rowan et al., 1988).

For the vinyl siding case, the results are presented in Figure 25 for the overall moisture losses. The high gain of total moisture by the sheathing is sufficient evidence that extended high-moisture conditions existed in the wall for the whole of the five-month simulation. Examination of the RH conditions in all layers behind the siding showed that little air exchange was taking place.

It was noted however, that the inlet and outlet leakage parameters specified for the top and bottom of the wall were the same as in the body of the wall. In practice, starter strips are normally used at the bottom of the wall. This permits some airflow to take place at that level. Other practical construction details at the top of walls are used to accommodate settlement of the structure, prevent buckling of the siding and assist in providing relief. No information was available for specifying the airflow characteristics for those details. It would appear that walls with vinyl siding might benefit from provision of greater venting. Knowledge of air leakage characteristics through vinyl siding joints and other practical details in their construction would be valuable.

Finally, in practice, when wind is directed against or along vinyl clad walls, flapping of the thin material can sometimes be heard. This is an indication that some dynamic pumping of air is taking place which would contribute to air exchange in the space behind the siding. While most analytical models cannot deal with these rapid dynamic effects, it may be possible to specify the airflow coefficients as a function of the wind velocity, wind direction and gust factor, a function that reverts to the conventional form under zero or near zero wind. This would involve testing to derive an empirical relationship for such a construct.

For the wood siding case, the results for a non-strapped wood siding wall with painted exposed faces and back-primed back faces are presented in Figure 26 for the overall moisture losses from the wall. Only this single figure is provided because one can infer most of the behaviour of this wall from this one plot.

The wood siding was initially specified to have 15 per cent moisture content which is high for a pre-finished primed product. Initially, there was some moisture loss from the siding but then, over a prolonged period, the moisture was regained and, at the conclusion of the five-month simulation, the siding retained more moisture than it started with. The OSB sheathing gained moisture because the moisture was redistributed from the studs. In fact, at one point, the inner face reached 45 per cent moisture content for a short while. The total moisture loss was low, even relative to that lost from the walls with stucco cladding. The air leakage coefficients built into this test wall do not provide for leakage at a starter strip, nor for that near the top of a wall with wood siding. The only coefficients provided represent those for tightly built wood siding. These results conform to expectations that the moisture retained would eventually cause paint peeling and more serious degradation of the siding.

Figure 25: Vinyl siding wall, drying from each of the major elements, chamber conditions at 70% RH and 5 C

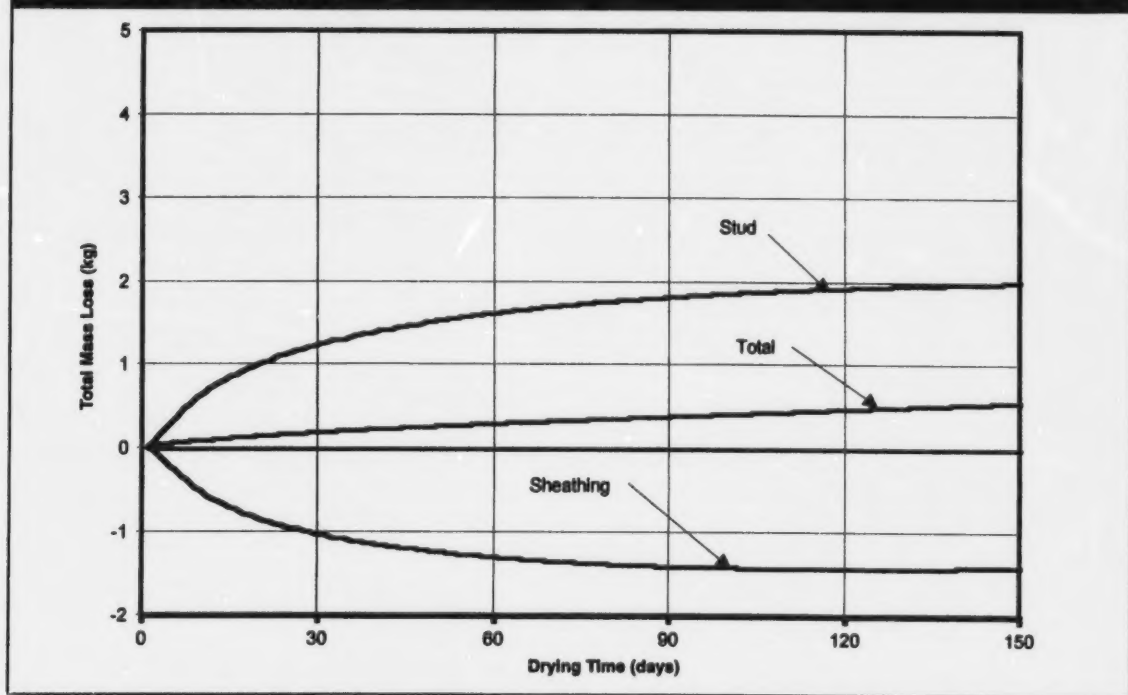
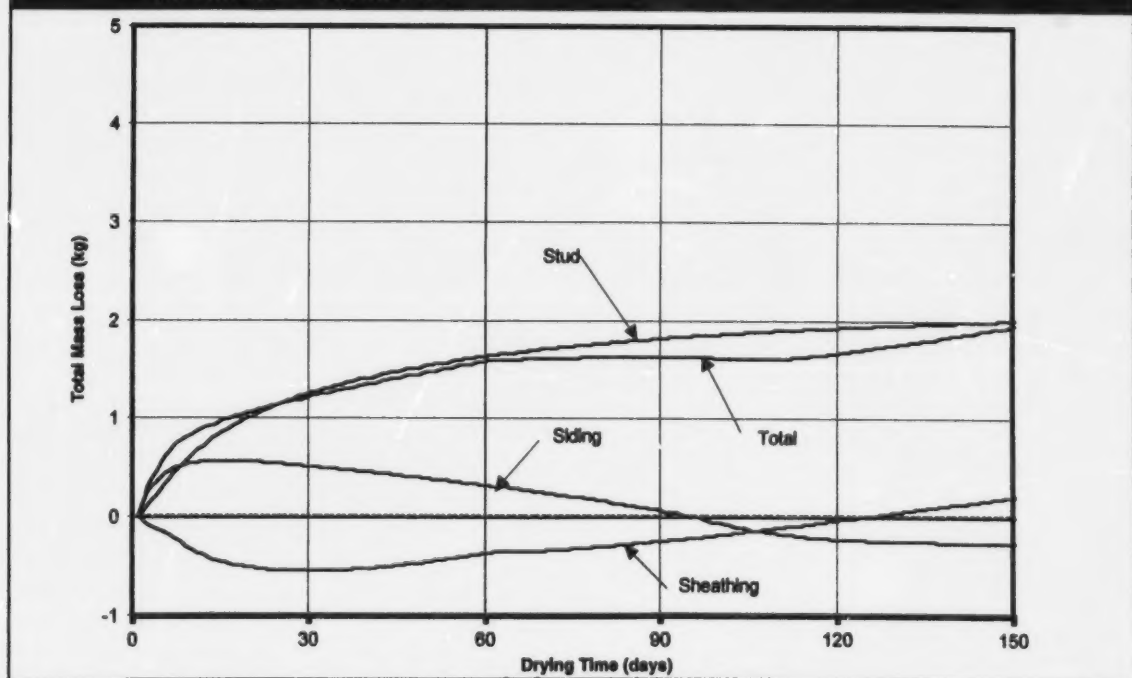


Figure 26: Drying from each major element in wall S19-12, polyethylene vapour barrier removed and top vent closed, chamber conditions at 70% RH and 5 C with stucco initially preconditioned at 50% RH



To illustrate the drying of the wall with strapped wood siding, the same coefficients are assumed for the siding in the field of the wall. To model the ventilation cavity, it is assumed that the siding is installed on 19-mm batten strips, with a 12-mm bottom vent and a 1-mm top vent restriction. The results were determined for a 5°C/70 per cent RH chamber, and are provided in figures 27, 28, 29, 30 and 31. The siding was permitted to assume equilibrium conditions for the 70 per cent RH chamber at the beginning of the simulation.

The typical total mass loss curves for each of the major elements in the wall are shown in Figure 27. The total mass lost was relatively high, and there appeared to be good drying from the studs and wall sheathing.

As the ventilation cavity and vent gaps provided were ample, there was a steady flow of air in the ventilation cavity. Figure 28 shows the variation in the RH of the air in that cavity from the bottom to the top of the wall. The air entering the bottom is slightly warmed, and the RH drops from the chamber conditions of 70 per cent. As the air moves up the wall, it is further

warmed and the RH drops even further. By the time the air has reached the top of the wall, it has picked up more moisture and its RH is raised.

The drying curves for the lumber shell and core in Figure 29 show that the face of the lumber dried rapidly, perhaps as rapidly as any previous plots of this type. This moisture first had to progress to the outside through the OSB sheathing, and the moisture content of the inner face of the sheathing is shown in Figure 30. The bottom element (representing one ninth of the wall height) was slower to dry than the mid-height or top element because the temperature of the air at the bottom of the ventilation cavity was cooler and the RH was higher. Similar variation on the outer face is shown in Figure 31 but the differences are not as marked. Not shown here are the variations in moisture content for the other portions of the wall. Despite the wet conditions in the wall itself, the movement of air in the ventilation cavity and through the individual siding laps was sufficient to maintain an equilibrium moisture content in the wood siding at very close to the initial equilibrium of between 11 and 12 per cent.

Figure 27: Drying from each major element in a wall with strapped wood siding with a 19-mm ventilation cavity, a 12-mm bottom vent and a 1-mm top vent, chamber conditions at 70% RH and 5°C with stucco initially preconditioned at 50% RH

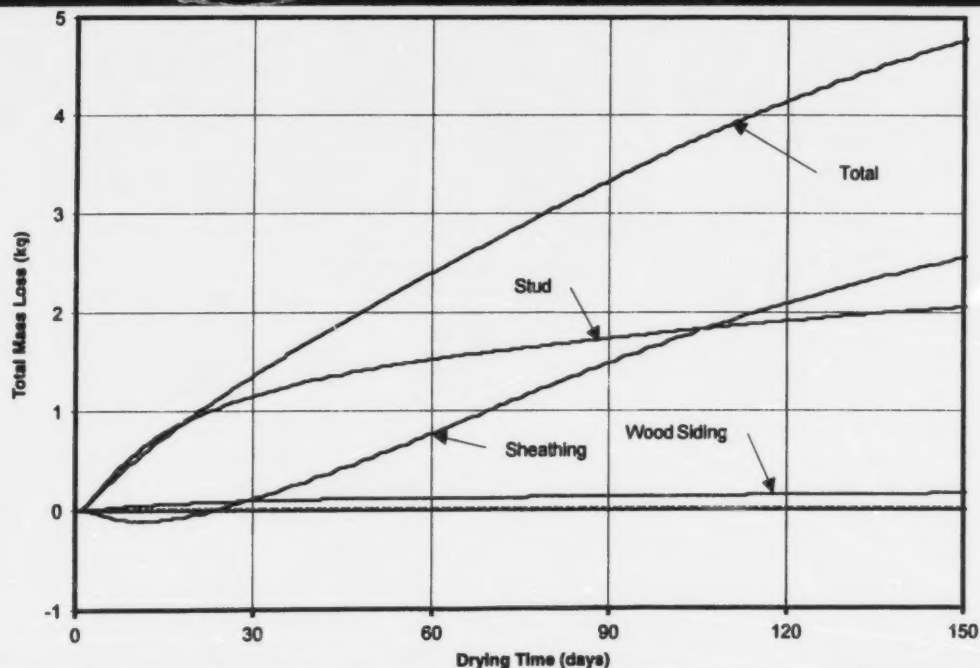


Figure 28: Relative humidity of air in the ventilation cavity, bottom to top: chamber RH of 70%.

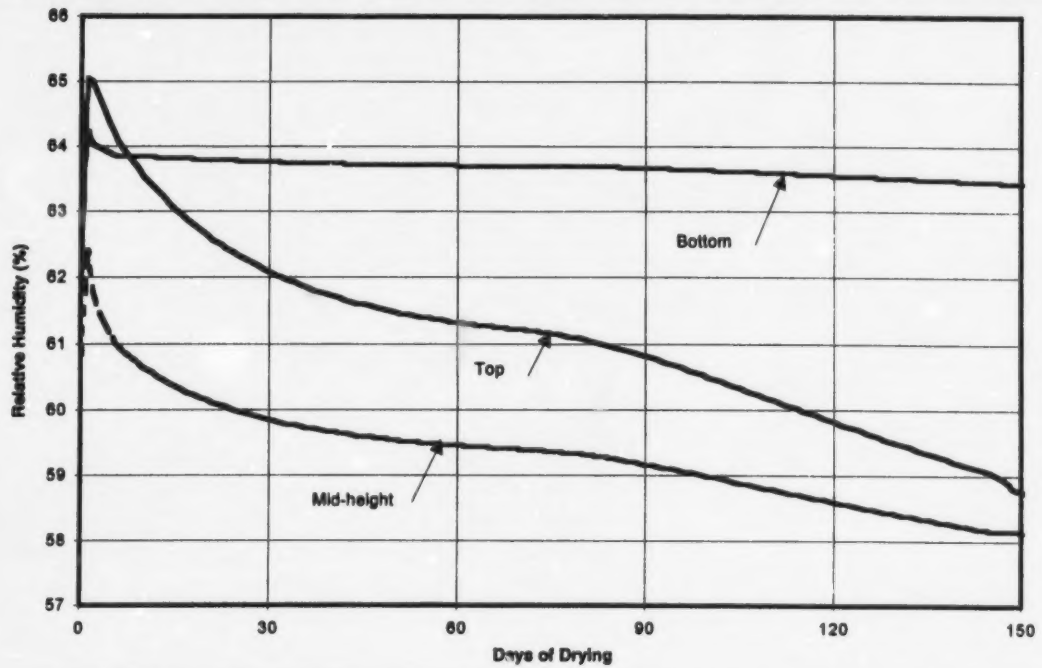


Figure 29: Drying of outer shell and inner core of the lumver framing, wall with wood siding on 19-mm batten straps, 12-mm bottom vent and 1-mm top vent

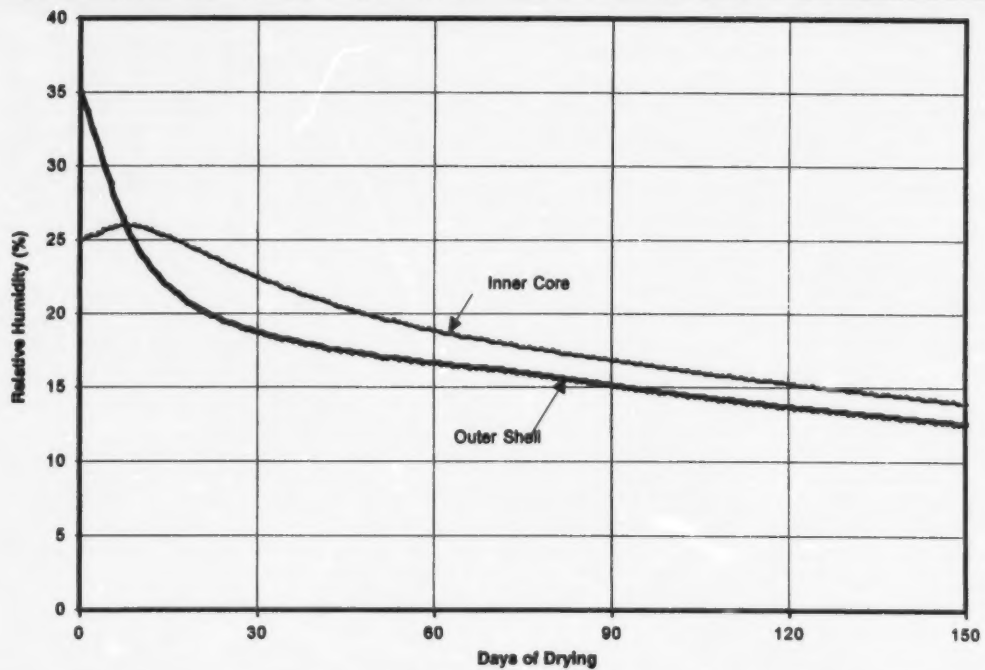


Figure 30: Drying curve for the inner face of the OSB sheathing, wall with wood siding on 19-mm ventilation cavity, 12-mm bottom vent and 1-mm top vent

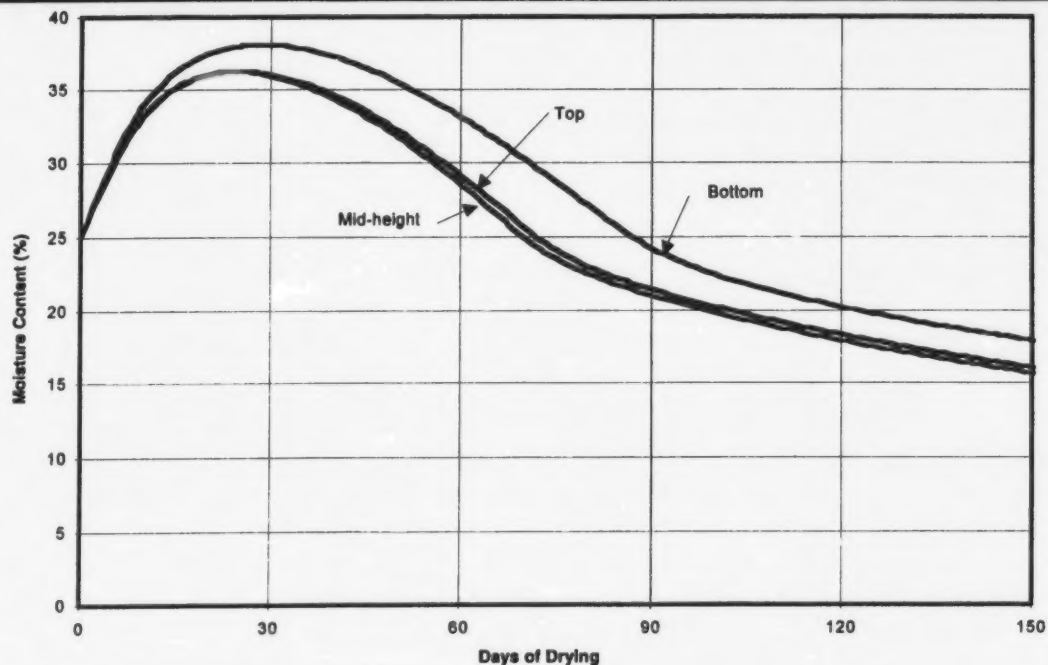
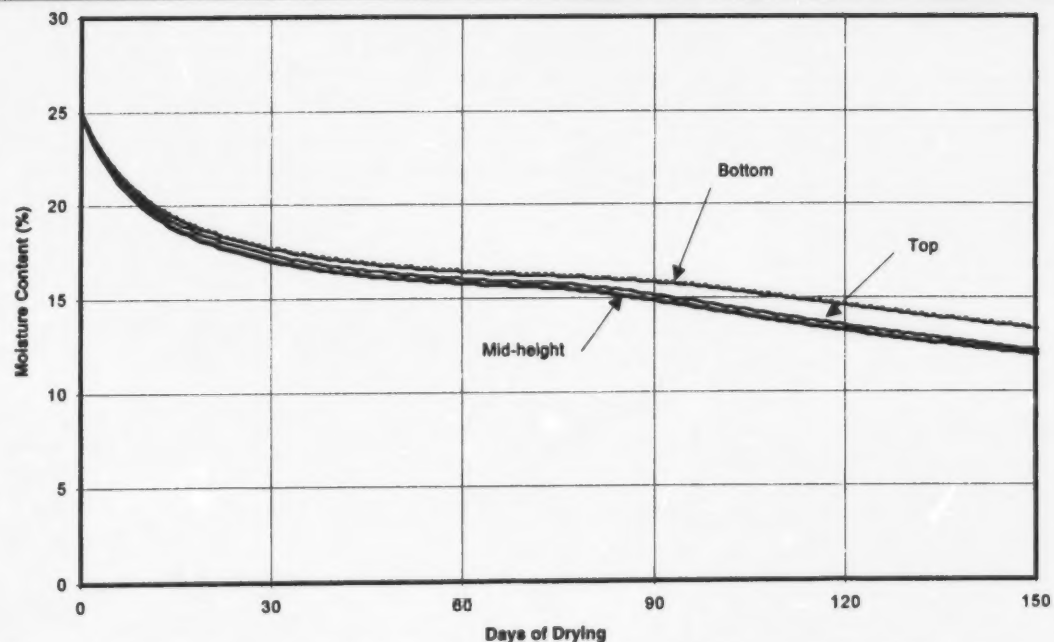


Figure 31: Drying of outer layer of OSB sheathing in wall with wood siding on a 19-mm ventilation cavity, 12-mm bottom vent and 1-mm top vent



11. CONCLUSIONS

This parametric study of the drying of stucco clad wall systems has examined a variety of situations to help understand the behaviour of outer wall venting systems. As well, other related matters linked to the EDRA experimental program, which will expose several wall system types to simulated steady-state weather conditions, were examined.

The main objective was to study ventilation cavity parameters for stucco wall systems using WALLDRY, a computer program developed by CMHC. A significant number of combinations of ventilation cavity depths and vent gap heights were included to assist the EDRA steering committee to decide on the final parameters for the experimental work. The following findings are noted.

1. The predominant detail affecting the rate of drying is the ventilation cavity depth behind the stucco. The vent gap height was not as critical to the rate at which moisture was removed.
2. The decoupled stucco cases (by specifying the properties of the stucco to be non-absorbent) provided a lower bound solution in drying rates for the investigation. Some types of stucco/backing systems may approach this case. The drying rates were slower than when the stucco was coupled to the wall (i.e., when the properties of the inner layer of stucco facing the wall were the same as for the outer face).
3. Typically, the coupled stucco case permitted both ventilation and diffusion of moisture to occur. But, when stucco was applied directly to the building paper against the wood sheathing, only diffusion permitted loss of moisture from the wall.
4. Closing the top vent of a vented stucco wall slowed drying significantly. However, it was demonstrated that even a slight amount of leakage (say that permitted by a 1-mm vent gap) was sufficient to approach the capability of a vented cavity with equal top and bottom vents.
5. From an experimental point of view, it was demonstrated that the moisture conditions of the stucco at the beginning of the study could interfere with interpretation of the drying rates of the wood wall behind. This was because the stucco could absorb or desorb large quantities of moisture depending on the equilibrium state of the stucco before exposure to the test chamber conditions. In other words, the total weight change of a wall does not provide all the information needed to characterize the drying capability of the wall.
6. The use of a lower RH condition in the chamber speeded drying of the test walls. A range of conditions from 50 to 80 per cent RH was provided to allow the EDRA team to decide whether a change in planned chamber conditions is warranted. A similar parametric evaluation was done for the temperature of the chamber.
7. Removal of the polyethylene vapour barrier allowed relatively rapid drying of the wall than when it was left in place. It was concluded that for a one-time construction moisture load, this might permit drying to take place during construction provided the final painting was not done until the moisture had escaped. Drying performance of the wall under chronic wetting is another matter entirely.

8. Vinyl siding appeared to retain the moisture in the sheathing for a significantly longer time than many coupled stucco walls. The airflow characteristics of the siding were based on properties evaluated in tests on small panels. These simulations did not include the effect of starter strips or practical closure details that might be found in the field—details that would improve the drying performance of walls. It was suggested that consideration to some venting would be beneficial for such walls. Pumping mechanisms related to the ability of the wind to flex the siding probably improves the drying capability of walls with vinyl siding. Some research is probably justified to characterize the equivalent leakage properties of these joints.
9. The wall with wood siding applied directly to it experienced as poor drying as the vinyl siding clad wall. In addition, direct contact with the wall allowed the siding to accumulate moisture. It has long been known that this can lead to degradation of the siding and prevent drying of the backup wall.
10. The wall with wood siding installed on batten strips and with provision of vents at the bottom, and limited venting at the top experienced good drying, and maintained the moisture content of the wood siding at moderately low levels.
11. The controlling element for moisture flow in all the parametric runs was the wood sheathing. The properties of the OSB material were assumed from information available in the literature. More recently, unpublished work suggests the properties of the OSB can vary significantly from one manufacturer to another. Consequently, the wood sheathing type and manufacture are critical matters to consider in choice of materials for the experimental work. The properties must also be well characterized for comparison with computer simulations.
12. Plywood sheathing has higher permeability than the OSB, based on test values available in the literature. Due to the manner in which initial moisture conditions were specified (in terms of bulk density), a comparison between them is not quite appropriate. However, it was concluded that plywood sheathed walls would probably dry more rapidly.
13. In the same vein, a comparison between the drying of 2 x 4 (38 x 89 mm) vs. 2 x 6 (38 x 140 mm) framed walls is complicated by the difference in total volume of wood framing and the total moisture that would be held in the wood for the same initial moisture content conditions. This comparison is appropriate when dealing with construction moisture, in which case, it was shown that a much greater volume of water had to be dissipated, and the concentration of that moisture in the sheathing was higher.
14. The variation in moisture content of the wood framing can vary rapidly at the beginning of the experiment, and it is necessary to be able to characterize the initial moisture gradients in the lumber. The variation in moisture up and down the wall is not expected to be very large in the lumber framing. However, drying from the bottom plate is expected to be slow. This was not modelled specifically in this study; however, based on the temperature gradients seen in this study as a result of movement of air behind the stucco cladding, the lower part of the test walls will dry more slowly than the top.
15. The moisture gradients through the thickness of the sheathing will be high. There will also be vertical moisture gradients in the sheathing due to the manner in which the moisture escapes at the top of the ventilation space, if one is provided.
16. The moisture content and absorption properties of the stucco are important influences on the weight measurement of the test walls. Any changing chamber conditions that affect the absorption and desorption of

moisture from the stucco may swamp the smaller changes in moisture content of the framing and sheathing of the test walls. In this case, if attempts are made to simulate solar effects, while the walls may dry more rapidly, there will be more complex moisture redistributions taking place. That would need to be adequately monitored for comparison with computer simulations, and to attribute adequately weight changes to this redistribution. There must also be sufficient instrumentation applied to assess how much moisture actually leaves the wooden elements in the wall.

17. Application of a simulated moderate wind speed directed at the test walls inside the test chamber resulted in greater cooling of the outer portions of the test walls. This slowed the rate at which moisture was lost by venting. The change was not large, and much depends on the airflow characteristics of the ventilation cavity and the vent gaps actually employed.

12. SUMMARY

The parametric study undertaken has provided some answers to the questions that might be asked of the performance of test walls subject to drying conditions in a test chamber. The important elements that must be monitored adequately to understand the moisture performance of the test walls were displayed, and the order of magnitude effects and drying rates should assist in the final

planning of the EDRA experimental program. Much will depend on the actual properties of the materials used. The experiment can serve for validation of computer models providing that adequate detailed information on moisture distribution is collected. Only then can deficiencies in modelling ability be ascertained.

13. RECOMMENDATIONS FOR FURTHER STUDY

The properties of stucco cladding included in the WALLDRY database were based on some preliminary testing by the IRC. Consultation with IRC scientists was necessary to assume properties that are close to those likely to be found in the field so the proposed computer simulations will be as realistic as possible.

Under some real weather conditions, with varying solar and exterior weather conditions, it may be possible that the relative ranking of the drying ability of walls, as determined from steady-state laboratory testing, may not hold. That eventuality should be assessed by computer modelling of a selected number of walls for the same assumed material properties and initial boundary conditions using real weather data in parallel with steady-state laboratory test conditions. If the ranking is seriously altered, this would throw into doubt the use of laboratory testing as a ranking tool in this manner. However, if that were the case, it would also suggest that the laboratory protocols might be altered to better simulate some of the effects that assist in driving moisture out of real walls.

The WALLDRY computer model does not currently include liquid mass transfer. The expansion of the modelling capability to include this moisture transfer mechanism is likely warranted. However, in its present form, it is not readily usable by the uninitiated because the previous user-friendly front end could not be used. The size of the program exceeded the capability of the QuickBasic compiler. Moving the program to a less limiting compiler is probably warranted, particularly as it may be useful to use this program to assess the performance of the walls in the upcoming experimental program.

During some simulations, instability in the airflow occurred. This is not entirely unexpected, either in practice or through the iterative solution approach. Of more concern was the "drift" in the solution for airflow velocity in some cases which did not correspond with expected performance. This artifact should be corrected. To this end, and for assessing other approximations in the program, it would be useful to compare the predictions by WALLDRY against the predictions of the more exact model LATENITE.

While the simulations described in this report correspond with general preconceptions of how walls perform under different conditions, it is only when verification studies are conducted that deficiencies in a model can be assessed and the model improved. The findings provided here are meant to guide experimenters concerning which parameters have sufficient difference to justify inclusion in an experimental program.

Thus, it will not be the place of this report to recommend which wall systems are worth investigation through laboratory studies. That will come from study of this report, and accounting for the interests of the EDRA consortium, and the magnitude of resources available to conduct the study. The main concluding recommendation that one might venture is that understanding the behaviour of test walls requires that the physical properties of the materials used be known and that related properties be measured in the test program. Knowing the initial boundary conditions and airflow characteristics is important to understanding how the walls will perform in the laboratory. This information is also useful for extrapolation to determine how test walls might have performed in the field under different conditions.

Appendix A

APPENDIX A: TYPICAL INPUT WALL FILE

S19-05 CMHC STUDY - STUCCO WALLS WITH CAVITIES - VANCOUVER NUMBER OF ROWS OF SIDING UP THE WALL (NV) AND LAYERS THROUGH THE WALL (NE) 9 20 NUMBER OF LAYERS OF SHEATHING: 2 OR 3 (USE 2 FOR LIGHT MATERIAL 3 FOR HEAVY) 3 W Y Y W Y Y SELECTION OF MATERIALS FOR EACH LAYER (SEE PROPERTIES DATA BASE FOR #) 1 15 28 28 28 4 5 4 6 6 11 11 11 17 17 17 19 21 4 9 THICKNESS OF EACH LAYER (in m)	1 .002 .005 .011 .005 .001 .019 .001 .0005 .0005 .003 .0065 .003 .003 2.966667E-02 2.966667E-02 2.966667E-02 .000127 .0127 .002 1 SELECTION OF MATERIALS FOR THE STUD LAYERS (SEE PROPERTIES DATA BASE FOR #) 18 18 LATERAL THICKNESS OF STUD LAYERS .019 .019 INITIAL MOISTURE CONTENT (%): SIDING, SHEATHING, STUDS 1 25 35 WALL HEIGHT (m), WALL LENGTH (m), No. OF EQUIVALENT FULL LENGTH STUDS, STUD LAYER LOCATION 2.44 1.22 5 15 Siding GAP Characteristics: K1 (Pa/(L/min)/m)) bottom to top (9 elements + opening) 5.205040673414866D-06
---	--

10000	1.7697E-07
10000	
10000	INWARD LEAK: ELEMENT # (0 IF NONE),
10000	ORIENTATION OF MAJOR LEAKS, WINTER
10000	AND SUMMER INDOOR
10000	TEMPERATURES AND RH
10000	0 360 20 20 40 40
10000	
7.738374670346578D-06	NUMBER OF THE AIR SPACE LAYER
	7
Siding GAP Characteristics: K2 (Pa/((L/min)/m)*)	
bottom to top (9 + opening)	(+/- 45) WIND PRESSURE COEFFICIENTS
5.205041E-06	bottom to top (9 elements + opening)
10000	45
10000	.2
10000	.15
10000	.12
10000	.1
10000	.095
10000	.09
10000	.1
7.738375E-06	.15
	.21
Siding AIR SPACE Characteristics: K1	.32
(Pa/gap)/(L/min/m)) bottom to top (9 elements +	
opening)	(+/- 90) WIND PRESSURE COEFFICIENTS
1.769700050354004D-04	bottom to top (9 elements + opening)
1.769700050354004D-04	90
1.769700050354004D-04	.02
1.769700050354004D-04	-.005
1.769700050354004D-04	-.0225
1.769700050354004D-04	-.0475
1.769700050354004D-04	-.0475
1.769700050354004D-04	-.055
1.769700050354004D-04	-.06
1.769700050354004D-04	-.035
1.769700050354004D-04	-.02
	.03
Siding AIR SPACE Characteristics: K2	
(Pa/gap)/(L/min/m) ²) bottom to top (9 +	
opening)	(+/- 135) WIND PRESSURE COEFFICIENTS
1.7697E-07	bottom to top (9 elements + opening)
1.7697E-07	135
1.7697E-07	-.16
1.7697E-07	-.16
1.7697E-07	-.165
1.7697E-07	-.175
1.7697E-07	-.19
1.7697E-07	-.2
1.7697E-07	-.22

-23	THREE MAJOR SUB MODELS
-25	3
-26	
(OTHER DIRECTIONS) WIND PRESSURE	NUMBER OF LAYERS DISPLAYED IN
COEFF bottom to top (9 elements + opening)	SCREEN (MAX 12); SPECIFY LAYER
180	NUMBERS
-18	12
-17	1
-16	2
-15	3
-15	5
-155	6
-155	7
-16	11
-15	12
-14	13
	21
	22
WALL ORIENTATION (DEGREES FROM	20
NORTH): N:360, E:90, S:180, W:270	
180	CITY LOCATION (1 - 10) SEE MANUAL
	1
MOISTURE SOURCE STRENGTH IN kg/hr,	
AND LOCATION: LAYER # AND ELEMENT	NAME OF OUTPUT FILE FOR PLOTTING
NUMBER	AND TABULAR OUTPUT(e.g., GRAPH.PRN)
0 10 6	S19-05.PRN
	S19-05.SUM
INITIAL WATER FILM THICKNESS TRAPPED	
BETWEEN SHEATHING PAPER AND	SIDING TIGHTNESS EQUATION FORM AND
SHEATHING	FLOW COEFFICIENTS AND EXPONENTS
0	3 0 0 0 0 0 0 0 0 0 0 0 0 0
NUMBER OF LAYERS FACING AIR (OR	
INSULATION), WHICH LAYERS	GRAPHICS AND TABULAR OUTPUT
8	CONTROLS
3	D
5	D
9	5 13 21 1 1 1
10	11 1
11	11 5
13	11 9
17	13 1
21	13 5
	13 9
	21 5
SIMULATION START AND END (DAY OF	22 5
THE YEAR)	3 5
1 1 160 24	5 5
	3
NUMBER OF ITERATIONS BETWEEN THE	

Appendix B

APPENDIX B: TYPICAL INPUT WEATHER FILE

FILE OF LABORATORY WEATHER FOR VANCOUVER SIMULATIONS Initial Stud (Moisture content, elements 1 to 9) 35 35 35 35 35 35 35 35 35 Leakage Characteristics - (formula $Q = C dP^n$), C is in (L/s) 0.0357 0.7 Condensation Infiltration/Exfiltration Transfer Efficiency 20 20 Field of Influence (J 1 to 9) - Exfiltration / Infiltration 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 Number of Hours, 192 Hour To Ti Rho Rhi Pressure Wind-V Wind- dir 1 5 20 70 40 0 0 0 2 5 20 70 40 0 0 0 3 5 20 70 40 0 0 0 4 5 20 70 40 0 0 0 5 5 20 70 40 0 0 0 6 5 20 70 40 0 0 0 7 5 20 70 40 0 0 0 8 5 20 70 40 0 0 0	9 5 20 70 40 0 0 0 10 5 20 70 40 0 0 0 11 5 20 70 40 0 0 0 12 5 20 70 40 0 0 0 13 5 20 70 40 0 0 0 14 5 20 70 40 0 0 0 15 5 20 70 40 0 0 0 16 5 20 70 40 0 0 0 17 5 20 70 40 0 0 0 18 5 20 70 40 0 0 0 19 5 20 70 40 0 0 0 20 5 20 70 40 0 0 0 21 5 20 70 40 0 0 0 22 5 20 70 40 0 0 0 23 5 20 70 40 0 0 0 24 5 20 70 40 0 0 0 25 5 20 70 40 0 0 0 26 5 20 70 40 0 0 0 27 5 20 70 40 0 0 0 28 5 20 70 40 0 0 0 29 5 20 70 40 0 0 0 30 5 20 70 40 0 0 0 31 5 20 70 40 0 0 0 32 5 20 70 40 0 0 0 33 5 20 70 40 0 0 0 34 5 20 70 40 0 0 0 35 5 20 70 40 0 0 0 36 5 20 70 40 0 0 0 ... etc.....
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Appendix C

APPENDIX C: DATABASE OF MATERIAL PROPERTIES - PROPS.DAT

33 , 7 , 40 , 40	SHEATHING PAPER
NAME	320
DENSITY (Kg/m3)	1,200
SPECIFIC HEAT (W.s)/(Kg.K)	10
THERMAL RESISTIVITY ((m2.C)/W)/m	6.5E11
DIFFUSION RESISTIVITY ((Pa.m2.s)/Kg)/m	25
MAXIMUM WATER ADSORPTION(%MC BY WEIGHT)	3
CLASS (1-AIR/2-WATER/3-WOOD/4-OTHER)	FIBREBOARD SHEATHING
OUTDOOR AIR	352
1.21	1,300
1,005	16.5
0	20E9
5.7E9	120
0	3
1	"STYROFOAM - SM"
WATER VAPOUR	30
.598	1,000
2,050	35
18.	1E12
0	30
0	4
1	INDOOR AIR
LIQUID WATER	1.21
998	1,005
4,180	0
1.66	5.7E9
0	0
0	1
2	PLYWOOD(DOUGLAS FIR)
INTERIOR AIR FILM	544
1.21	1,220
1,005	8.7
60	3906E9
5.7E9	60
0	3
1	ORIENTED STRAND BOARD
AIR SPACE	670
1.21	1,300
1,005	7.4
15	0.8E12
5.7E9	45
0	3
1	SEMI-RIGID FIBREGLASS
	100

960	0
30.5	3
5.9E9	2.1E16
30	1
4	4
HARDBOARD SIDING	PAINTED WOOD SIDING
800	544
1,300	1,170
10.7	11.9
503E9	3E12
40	30
3	3
METAL SIDING	GYPSUM
2,740	1,200
896	1,080
.004	2.33
1E20	15.75E9
10	280
2	4
EXTERIOR AIR FILM	POLYOLEFIN
1.21	533
1,005	1,300
15	10
5.7E9	4.44E12
0	2
1	4
WOOD-BASED SIDING	HARDBOARD SIDING (S)
544	800
1,170	1,300
11.9	10.7
800E9	18E9
60	40
3	3
GLASS BATTS (L)	FIBREBOARD SHEATHING (S)
25	352
657	1,300
13	16.5
5.9E9	6.6E9
30	120
4	3
WOOD STUD	VINYL SIDING
375	620
1,200	946
9.1	
800E9	6.2
60	.2E15
3	2
POLYETHYLENE	4
920	BEAD BOARD (TYPE 2)

29	2E14
1,000	1
28	4
.32E12	STUCCO (PAPERBACK)
33	190
4	1,200
BRICK	10
1,970	6.5E11
800	40
1.43	4
.2E12	STUCCO (PLYBACK)
20	550
4	1,220
STUCCO (UNCOATED)	8.7
2,000	3906E9
700	60
1	3
2.1E11	STUCCO (GEOTEXT)
2	100
4	500
STUCCO (ACRYLIC)	500
900	9E9
0	120
4	4

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